

The CDF Silicon Vertex Trigger

Motivation
Key techniques
First physics results
Looking to the future

Bill Ashmanskas
U. Chicago

Why a hadronic B trigger at CDF?

Why study bottom (and charm) decays?

Why at CDF?

Why do you need a trigger?

Why select based on lifetime information?

Why study bottom and charm decays?

Study weak interactions of quarks

- map out CKM matrix
- \exists ? CP violation not explained by single CKM phase?

Study strong interactions

- one observes hadrons, not free quarks: how to relate?
- masses, exclusive lifetimes, ..., test low Q^2 QCD
- validate methods for non-perturbative calculations

Search for rare or forbidden processes

- new particles may appear through loop diagrams
 - aim for distinctive modes whose SM rates are small

Why at CDF?

Large cross-section

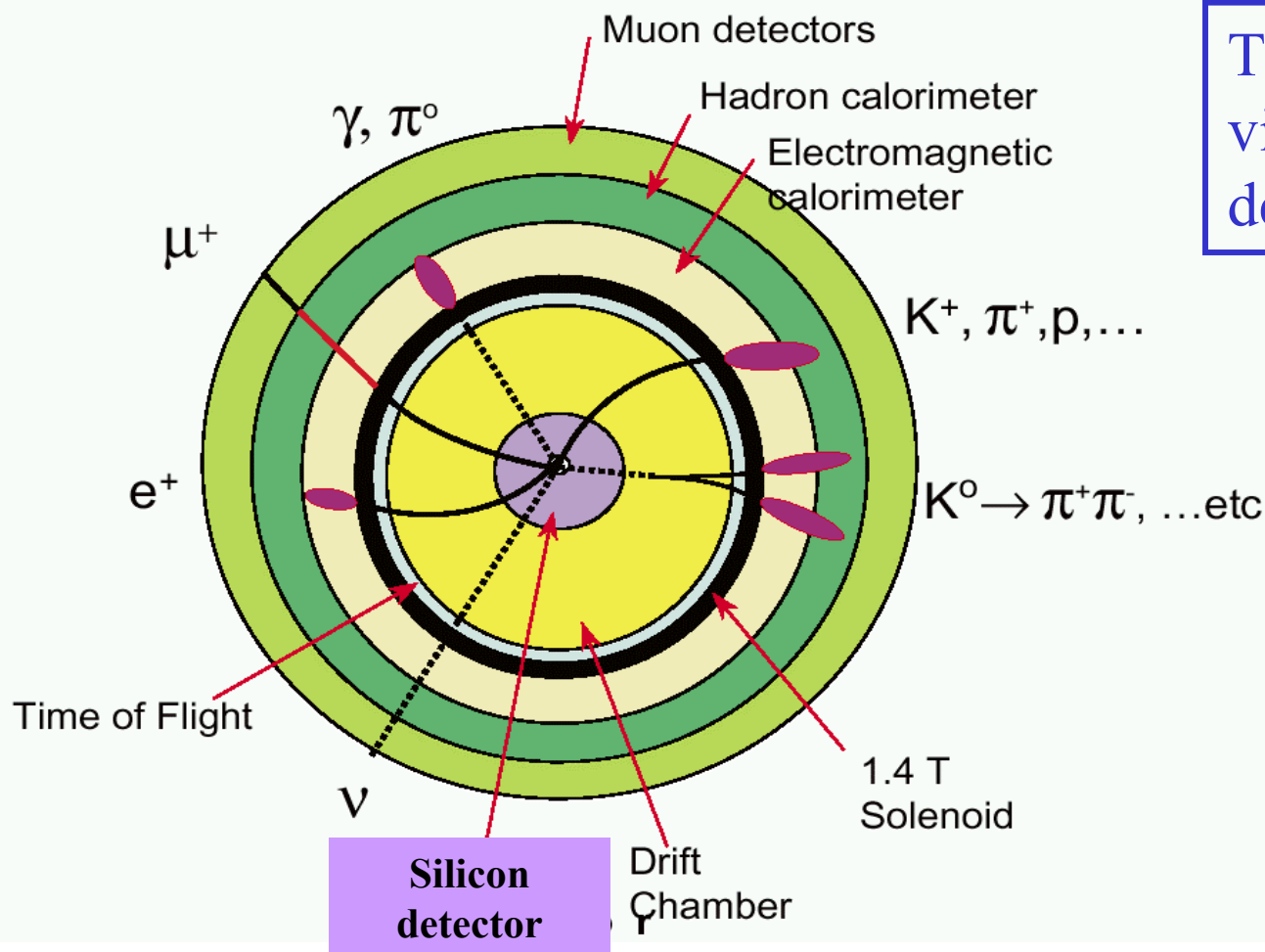
- $\sigma(bb) \sim 100\mu\text{b}$ (10kHz @ E32)
- $\sigma(B^+, |y|<1, p_T>6) \sim 3\mu\text{b}$ (300Hz @ E32)
- compare: $\sigma(bb) \sim 1\text{nb}$ at Y(4S) (5Hz @ 5E33)

Produce all states: B^0 , B^+ , B_s , Λ_B , B_C

Down side:

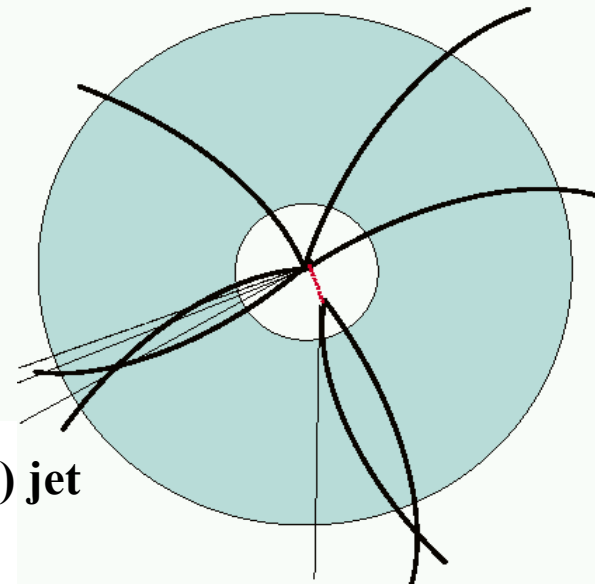
- Proton is a broad-band beam of partons: don't know initial state, no Pbeam constraint
- Second b often escapes
- Underlying event
- Non-b backgrounds difficult to model

Particle signatures at CDF



Transverse
view of
detector

generic (u,d,s) jet



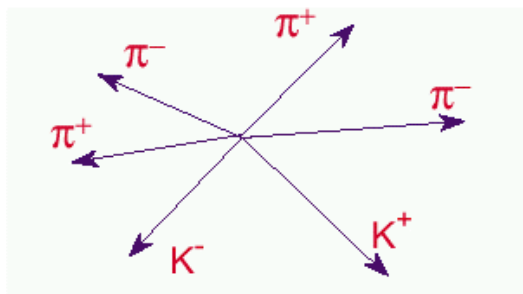
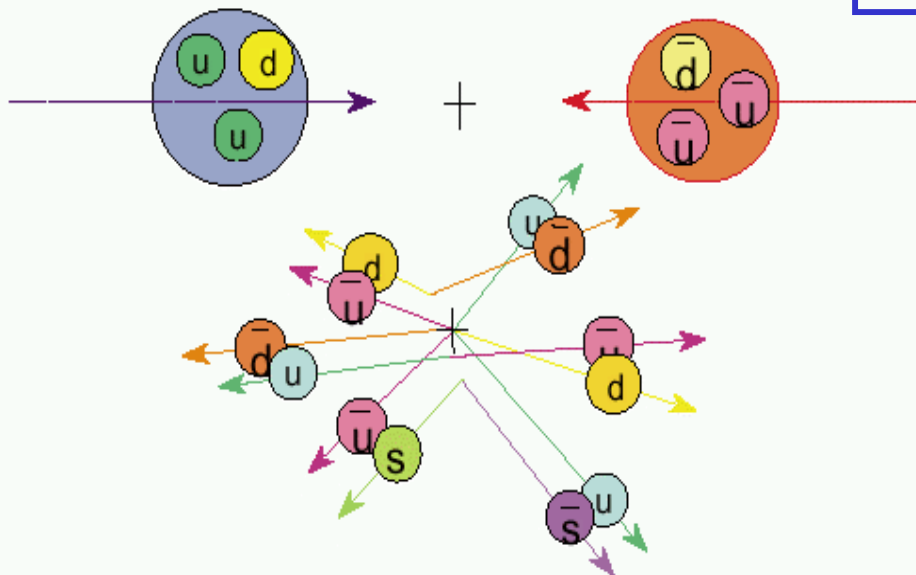
b,c jet

Why do you need a trigger?

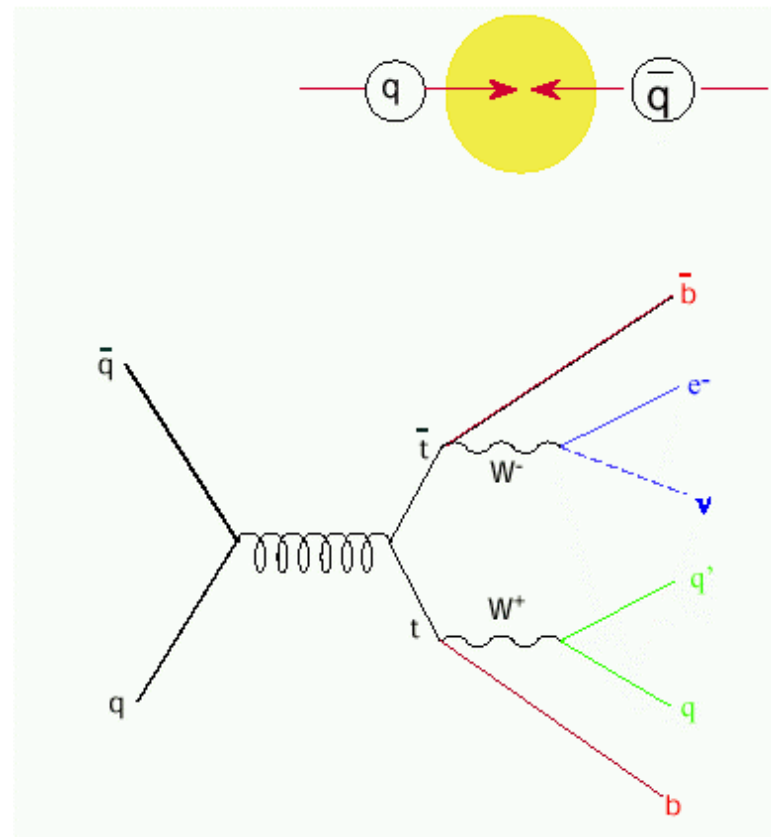
Haystack

R-Z view

Needle

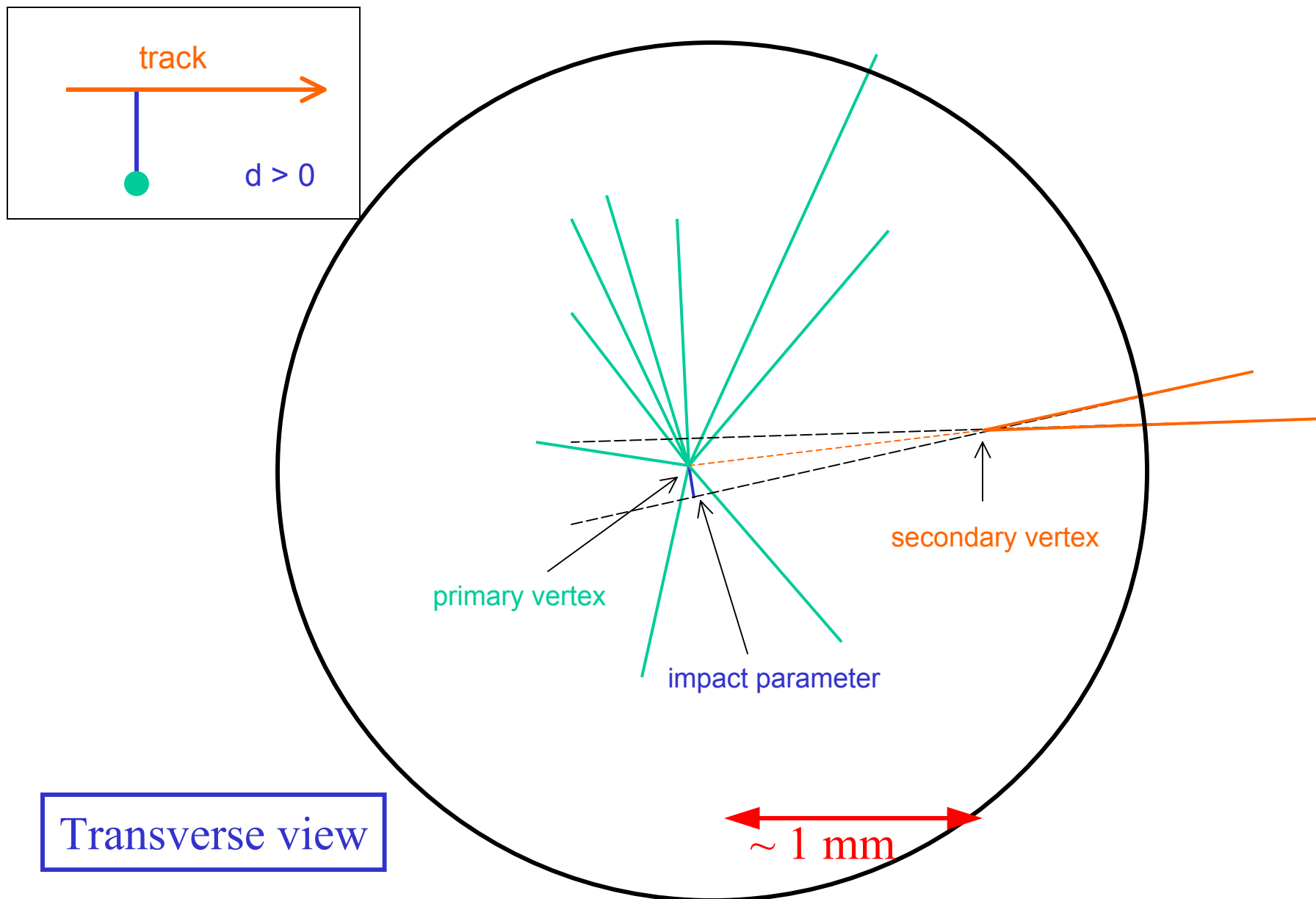


Vast majority of collisions; a democratic trigger would see only this



$\times 10^{10}$ less frequent: top quark pair production

A salient property of b,c decay: lifetime



Division of labor: 3-step selection

Three levels of detail (foundation, framing, finish carpentry)

- Different technologies appropriate for different steps

2.5 MHz



25 kHz



250 Hz



50 Hz

Level 1: (backhoe, cement truck)

- 5.5 μ sec, synchronous, fast programmable logic
- calorimeter cells, muons, drift chamber tracks

Level 2: (pneumatic nailing gun, circular saw, power ladder)

- ~ 30 μ sec, asynchronous, programmable logic + CPU
- jet clustering, silicon tracking

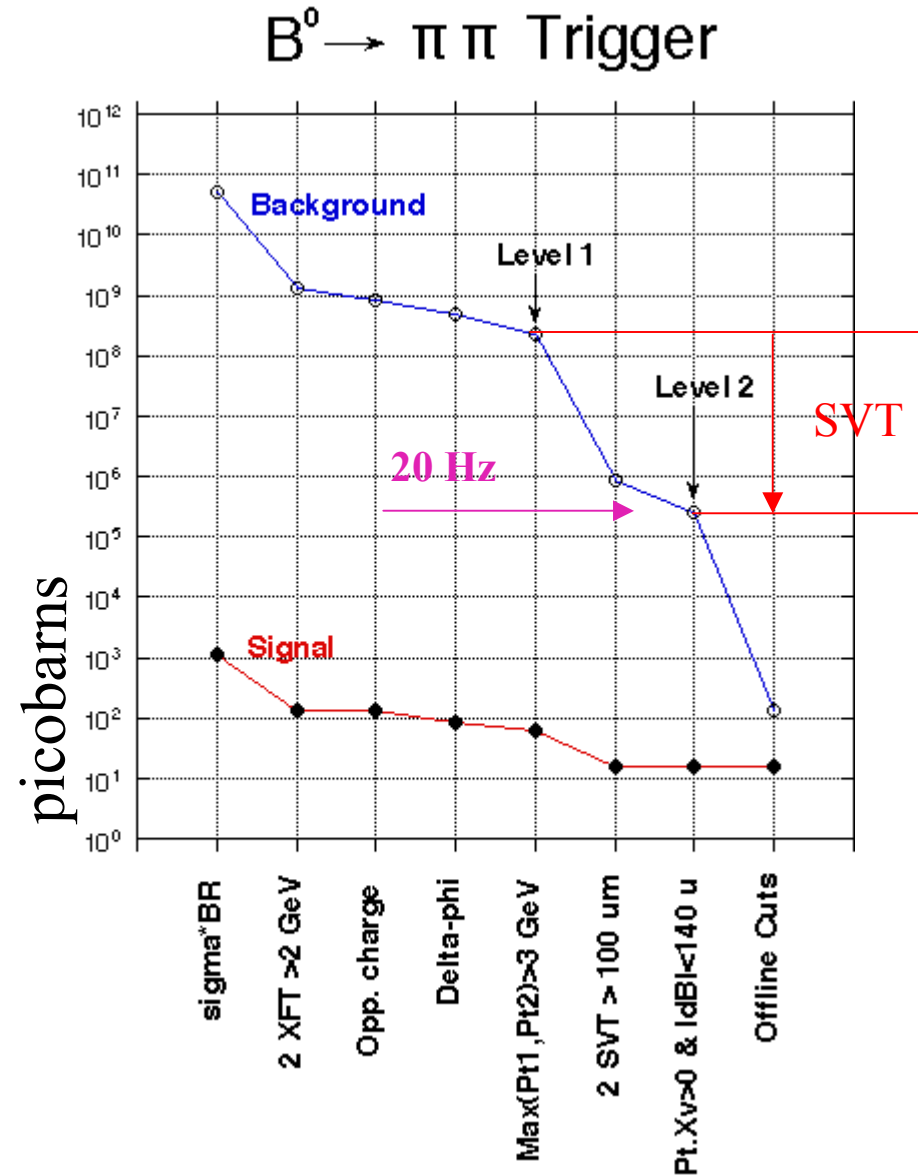
Level 3: (hammer, finish nails, miter box)

- ~ 200 commodity PC's spend ~ 1 sec/event on \sim full reconstruction
 - full-precision tracking, form masses, etc.
- ~ 140 separate trigger paths (e, μ , τ , ν , γ , jet, displaced track, b jet, ...)

SVT for $B^0 \rightarrow \pi^+ \pi^-$

SVT reduces the background rate by a factor of 1000

- data recording possible by DAQ



Introducing ... S V T

Both the name and the details of the physics goals have evolved over time ...

CDF/DOC/TRIGGER/PUBLIC/1421
SVT
THE SILICON VERTEX TRACKER
 Luciano Ristori
 May 1, 1991

“trigger”

CDF Note 1421
 by L. Ristori

May 1st, 1991

INTRODUCTION

This note describes the architecture of a device we believe we can build to reconstruct tracks in the Silicon Vertex Detector (SVX) with enough speed and accuracy to be used at trigger level 2 to select events containing secondary vertices originated by B decay. We name such a device *Silicon Vertex Tracker* (SVT).

The use of SVT as part of the CDF trigger would allow us to collect a large sample of B's ($> 10^7$ events) in a 100 pb^{-1} run.

B production at 2 TeV in the c.m. is abundant: Isajet predicts that, in the central region, 6.5% of two-jet events with $P_T > 20 \text{ GeV}/c$ contain a B pair. Thus we need a trigger with a relatively modest rejection factor ($10 \div 20$) not necessarily requiring the presence of very high P_T tracks.

It turns out that the simple requirement of a single track with an impact parameter greater than a given threshold might do the job.

The possibility to use the output of SVT to actually reconstruct secondary vertices is left open and it's not discussed here.

In Section 1 we report the results of some simple simulations we have done to show the efficacy of the impact parameter cut, in Section 2 we overview the overall architecture of SVT, in Section 3 we describe the different parts SVT is made of and how they relate to the different stages the track finding process goes through.

1. SIMULATION RESULTS

1.1 Impact Parameter Cut

The impact parameter s of each track is defined as the minimum



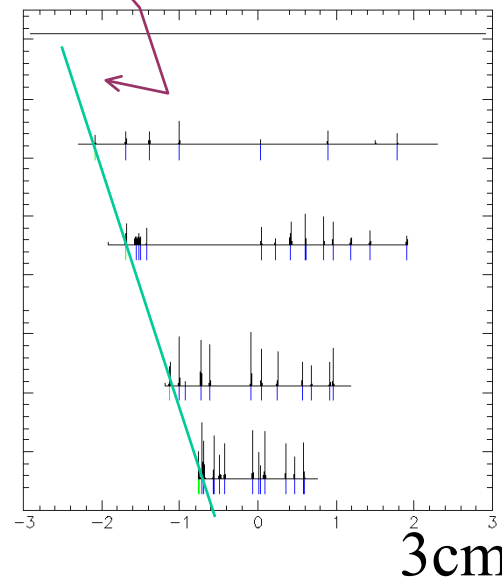
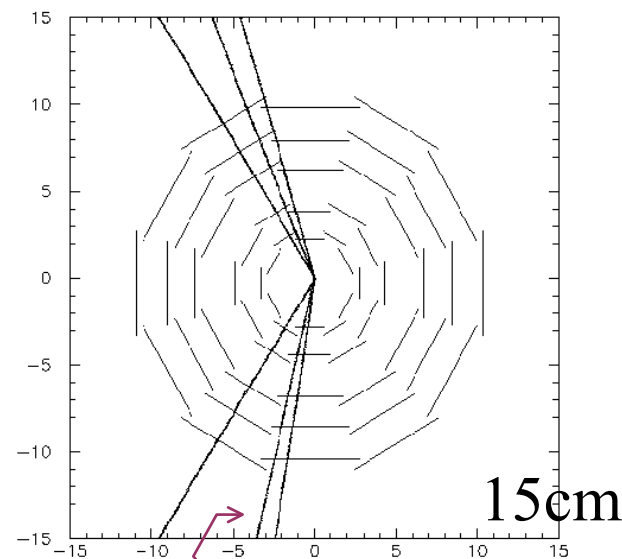
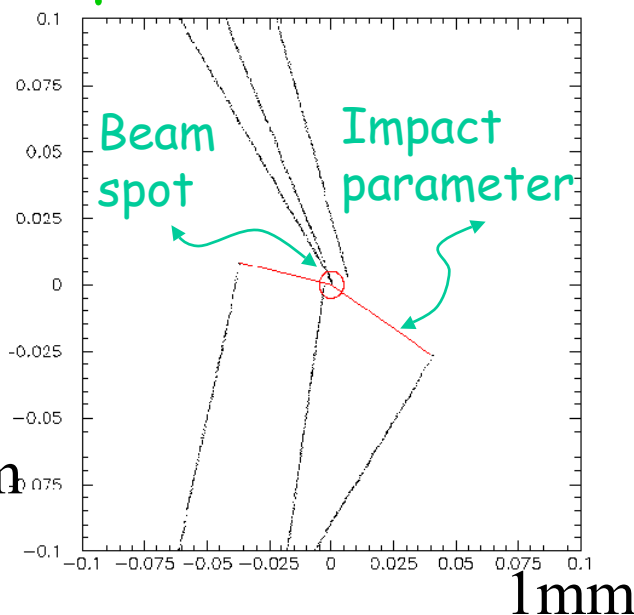
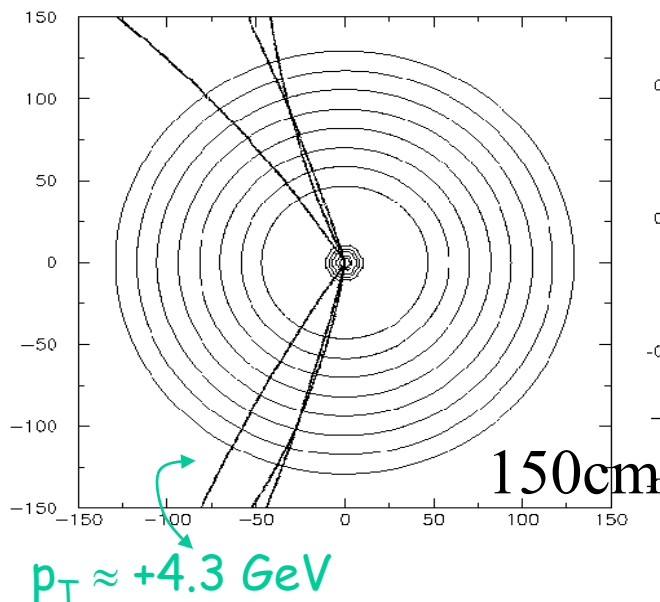
Problem synopsis

Available input:

- list of L1 drift chamber tracks of $P_T > 1.5 \text{ GeV}$
 - $\sigma(q/P_T) = 1.7\%/\text{GeV}$, $\sigma(\phi) = 5 \text{ mrad}$
- silicon raw data (pulse height for each channel)

Desired output:

- tracks combining chamber + silicon points
 - $\sigma(q/P_T) = 1.0\%/\text{GeV}$, $\sigma(\phi) = 1.5 \text{ mrad}$, $\sigma(d) = 35 \mu\text{m}$
- **and we need it in $\sim 15 \mu\text{s}$**



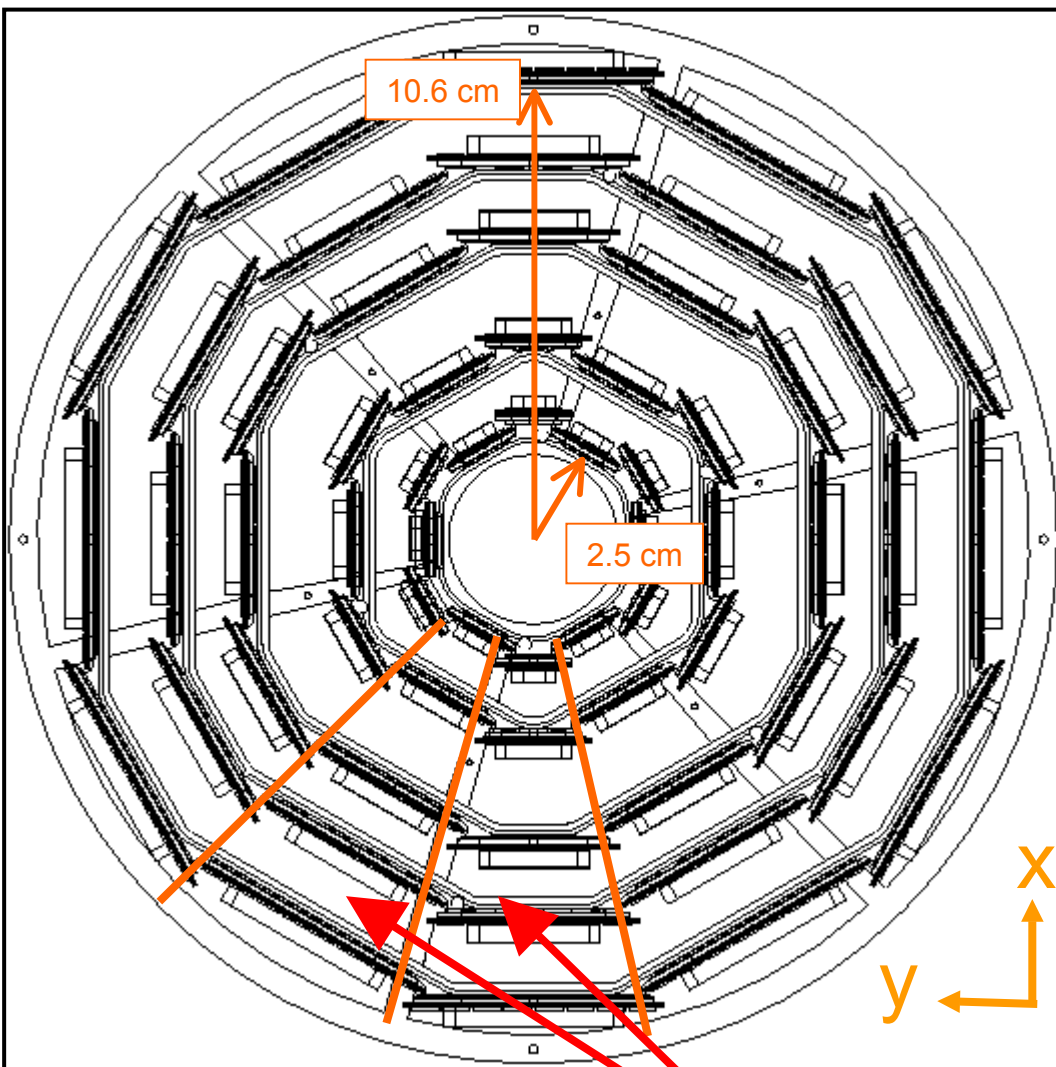
Three of SVT's key techniques ...

How do we do silicon track reconstruction in about 15 microseconds?

- (1) Do everything you can in parallel and in a pipeline.
- (2) Streamlined pattern recognition
 - Bin coordinate information coarsely into roads.
 - Examine all possible patterns in parallel (of course).
 - This is done in a custom VLSI chip.
- (3) Linearize the fitting problem.
 - i.e. solvable with matrix arithmetic

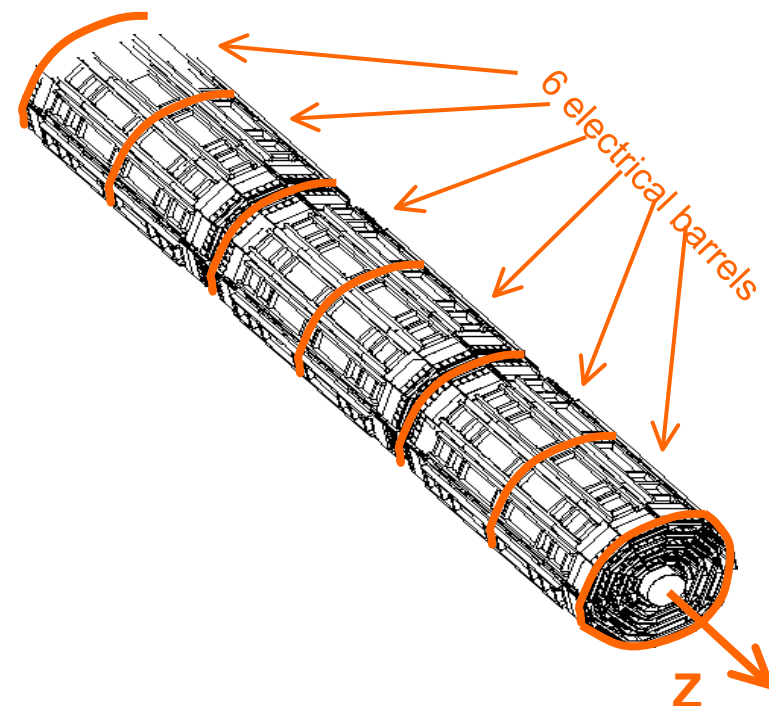
The wisest are the most annoyed by the loss of time. -Dante

SVX-II: symmetry allows parallelism



Note "wedge" symmetry

Symmetric, modular geometry lends itself to processing in parallel

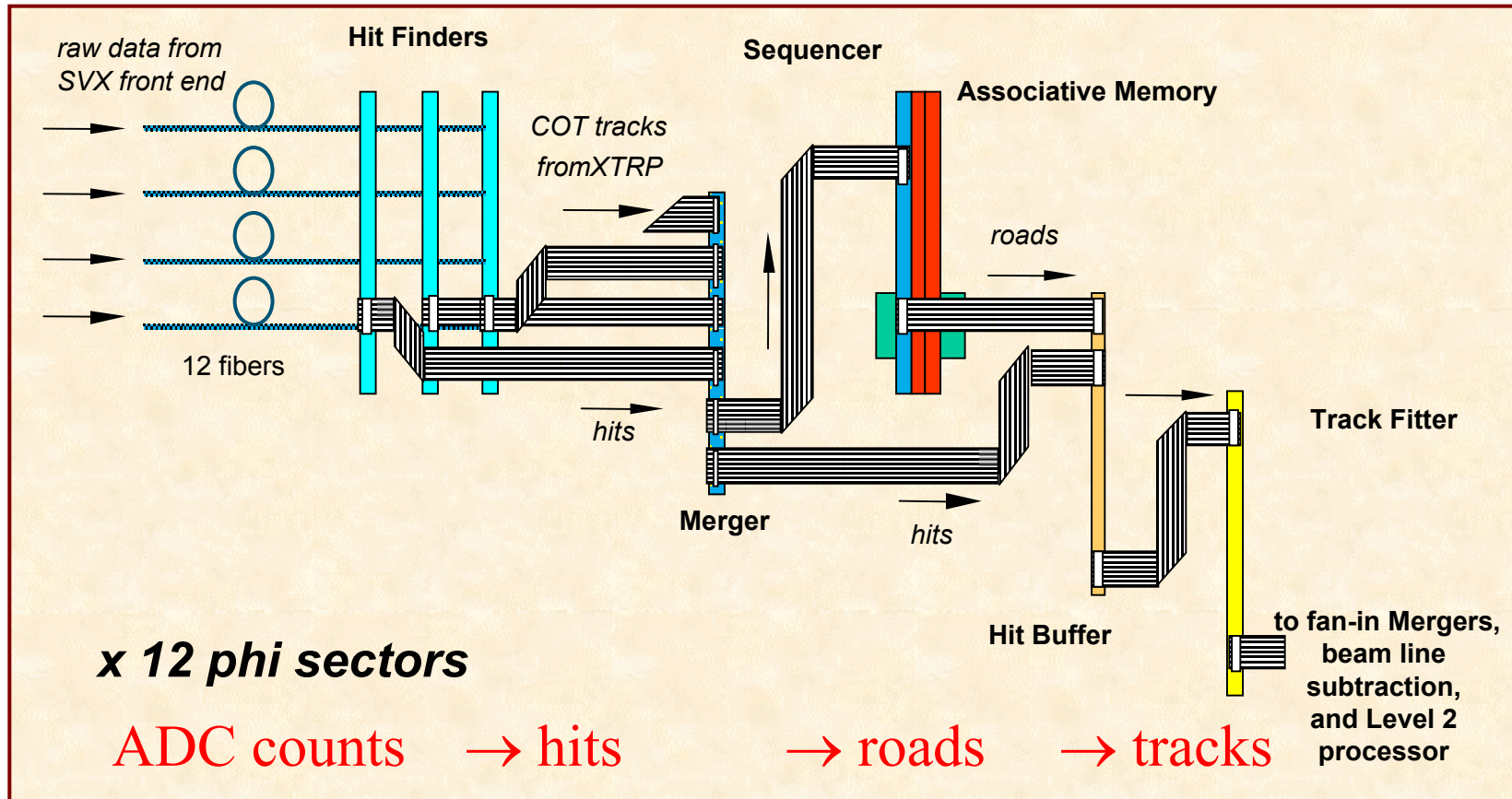


SVT data volume requires parallelism

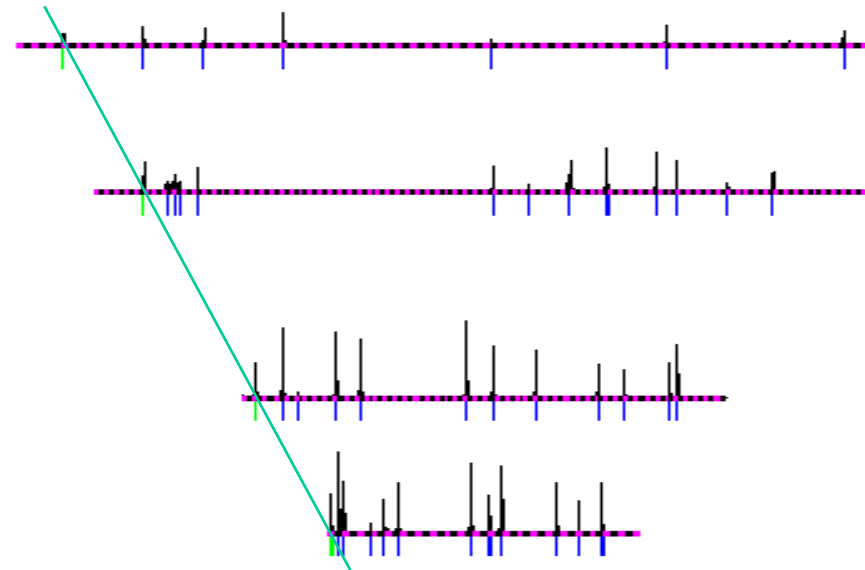
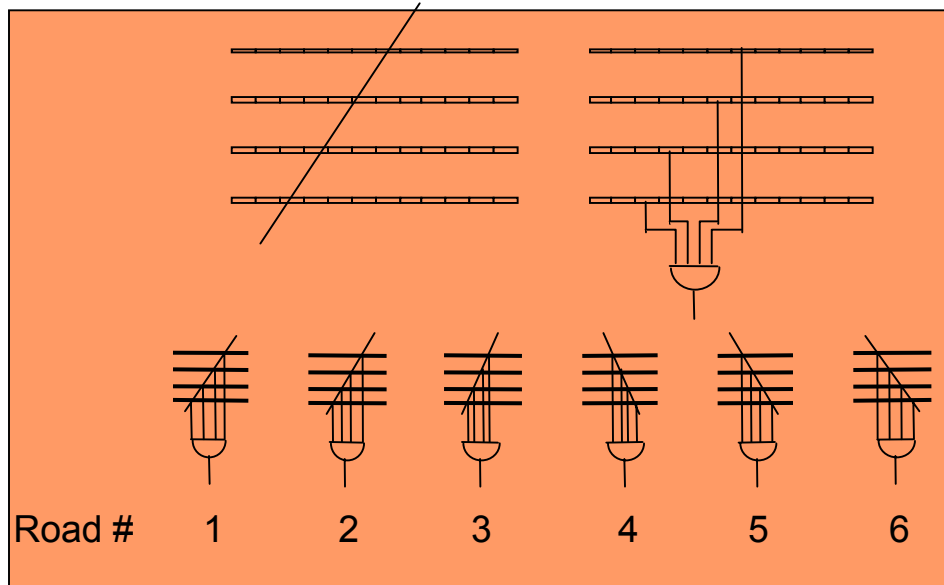


Reduces gigabytes/second to megabytes/second

SVT: 12-fold (azimuthally) symmetric and pipelined



2nd key technique: streamlined pattern recognition



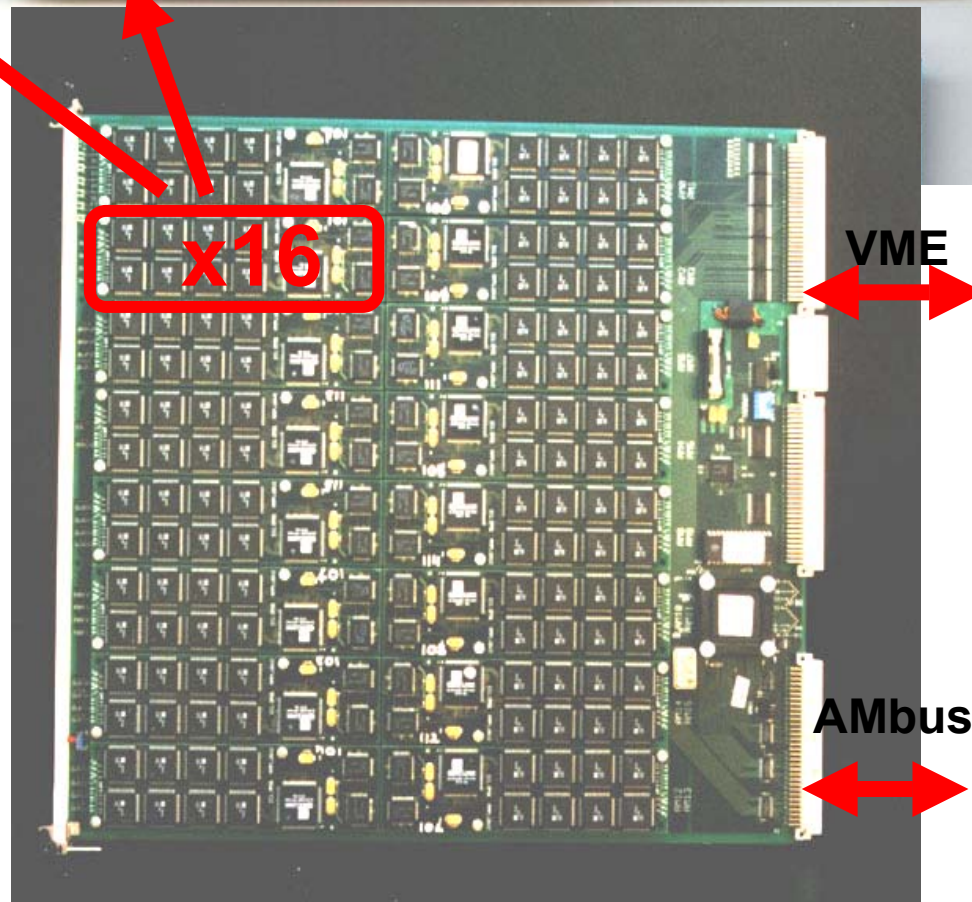
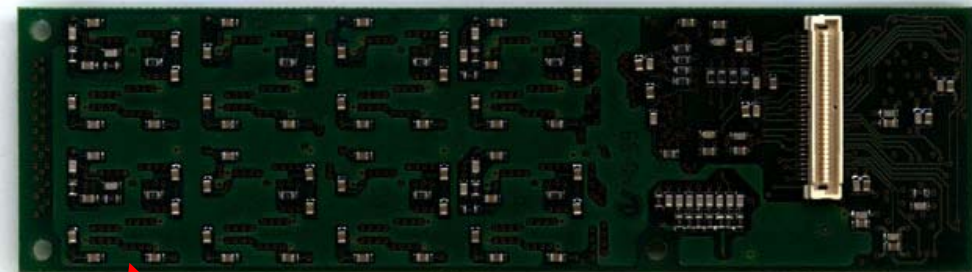
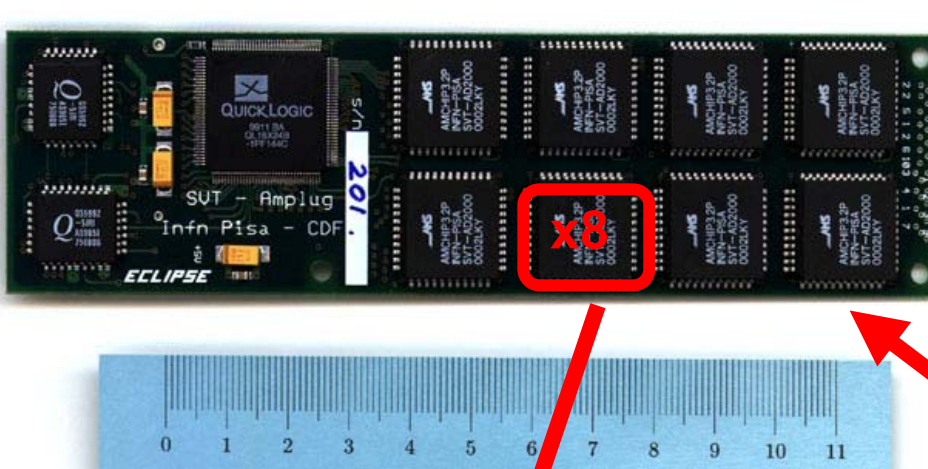
The way we find tracks is a cross between

- the “histogram search” software tracking algorithm
- the BINGO game

$$\text{Time} \sim A \cdot N_{\text{hits}} + B \cdot N_{\text{matchedroads}} + C$$

B	I	N	G	O
2	17	35	48	61
10	21	39	53	66
14	20	free	55	65
8	25	41	52	62
6	16	37	46	67

Our colleagues invested *years* in this Bingo game!



Trick #3: linear fit within 30° wedge

Why / how well it should work:

For a circle tangent to the x axis,

$$y = \frac{cr^2 + d(1 + cd)}{1 + 2cd}.$$

Including $\phi \neq 0$ and using $|cd| < 10^{-4}$,

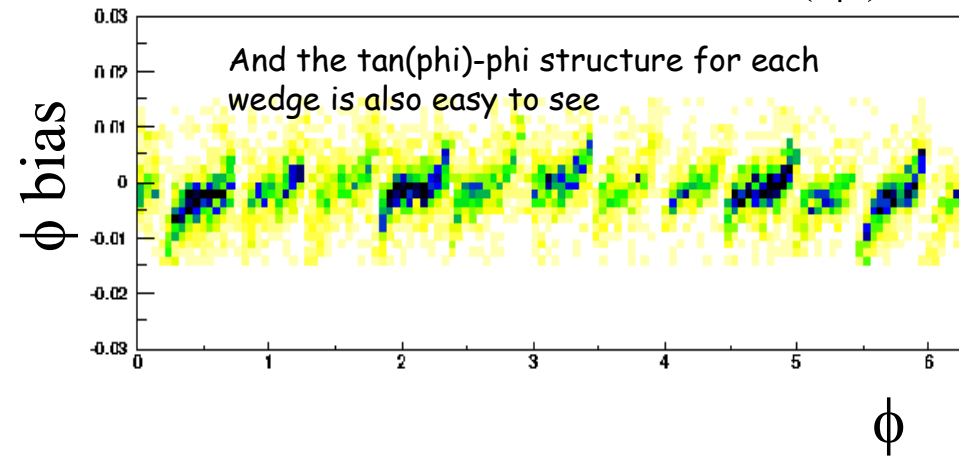
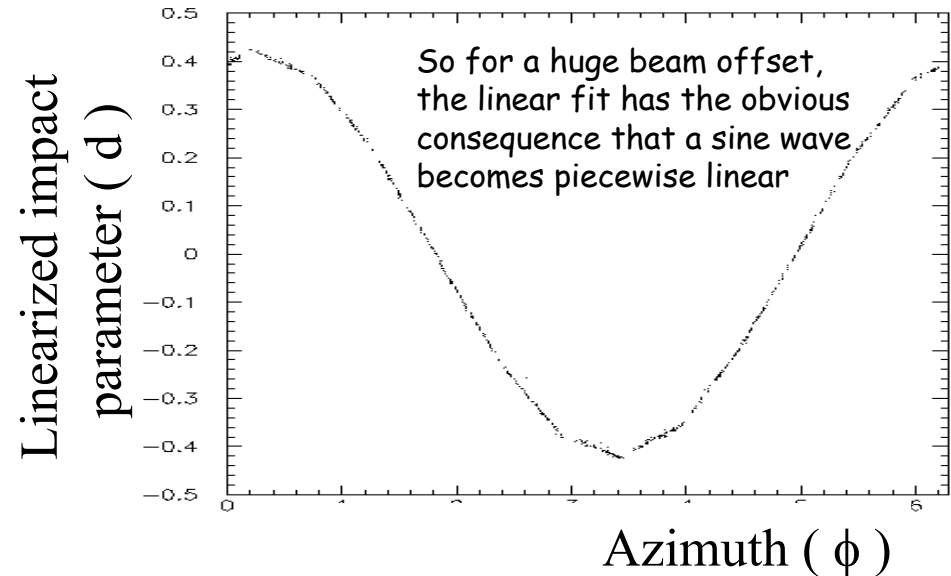
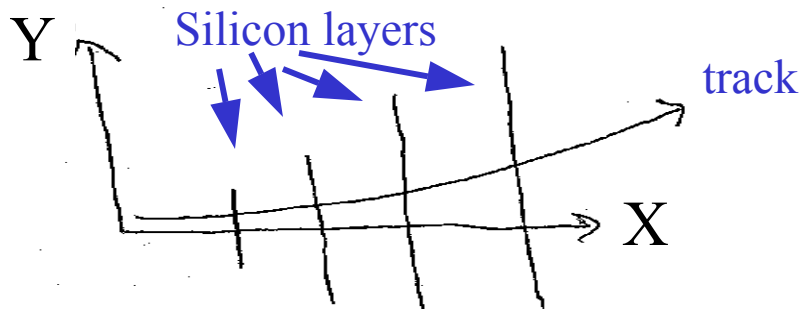
$$y = \frac{cr^2}{\cos \phi} + r \sin \phi + \frac{d}{\cos \phi}.$$

Silicon: constant x , not constant r :

$$y = \frac{c}{\cos^3 \phi} x^2 + x \tan \phi + \frac{d}{\cos \phi}.$$

\Rightarrow

- (1) Fit is linear in $\tan(\phi)$, not ϕ
- (2) up to 3.5% scale error on d :
3.5 μm at 100 μm (at 15°)



Track fitter: fast, linearized fitting

Tsuyoshi Nakaya, Un-ki Yang, et al, U. Chicago

Input (x): 4 hits + $c, \phi \equiv x$

Output: c, ϕ, d, χ^2 :

$$(c, \phi, d, \chi_1, \chi_2, \chi_3) = \vec{p} = \vec{p}_0 + V \cdot \vec{x}$$

The 6 scalar products are
computed in parallel

Using road ID as a hint,
multiply is reduced to 8 bits:

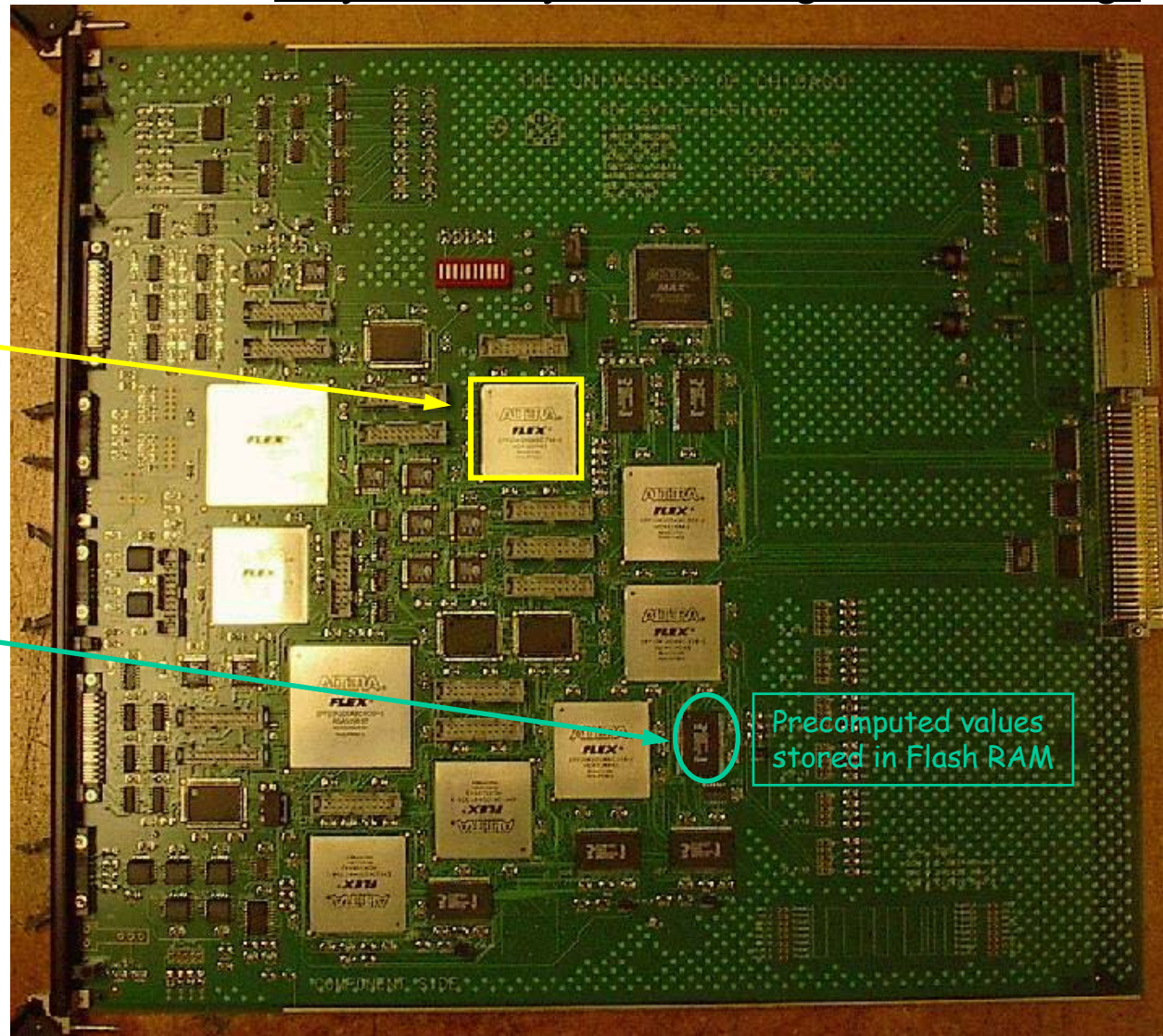
$$P_0 + V \cdot X =$$

$$(P_0 + V \cdot X_{\text{road}}) + V \cdot (X - X_{\text{road}})$$

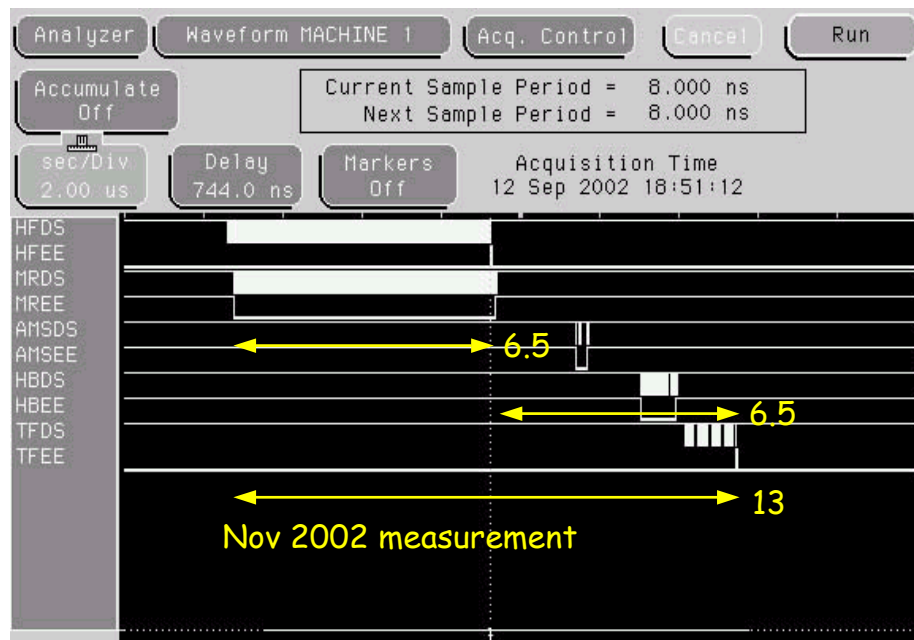
Each fit done in 250 nanosec

➤ fast programmable logic

Fits passing χ^2 cut are sent
downstream



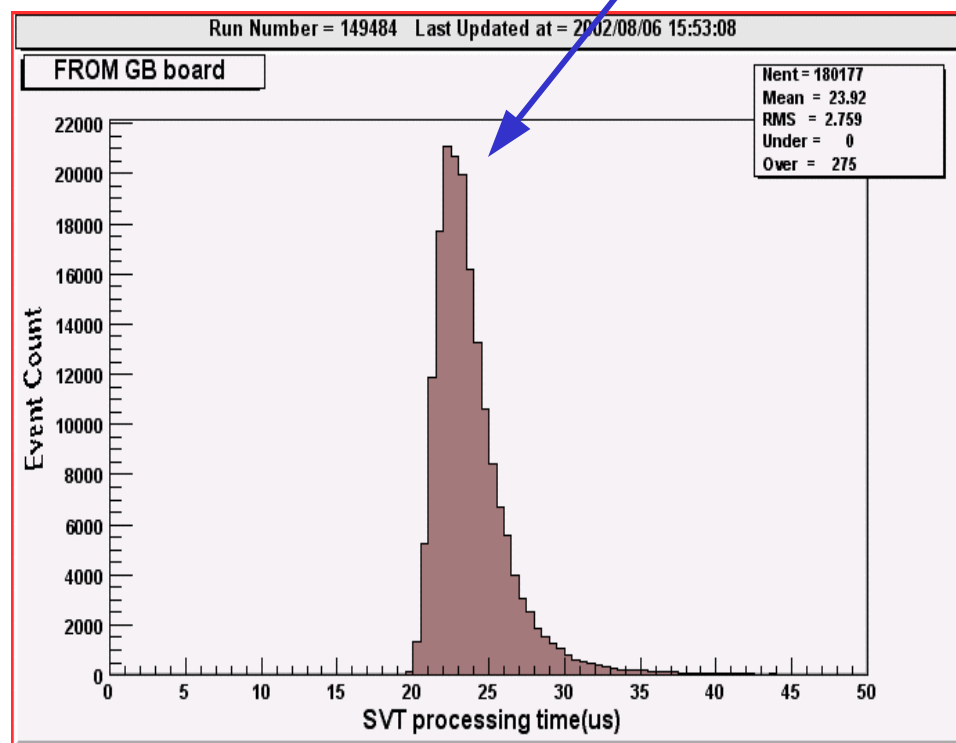
~10 μ s waiting for data, ~15 processing, and we're done!



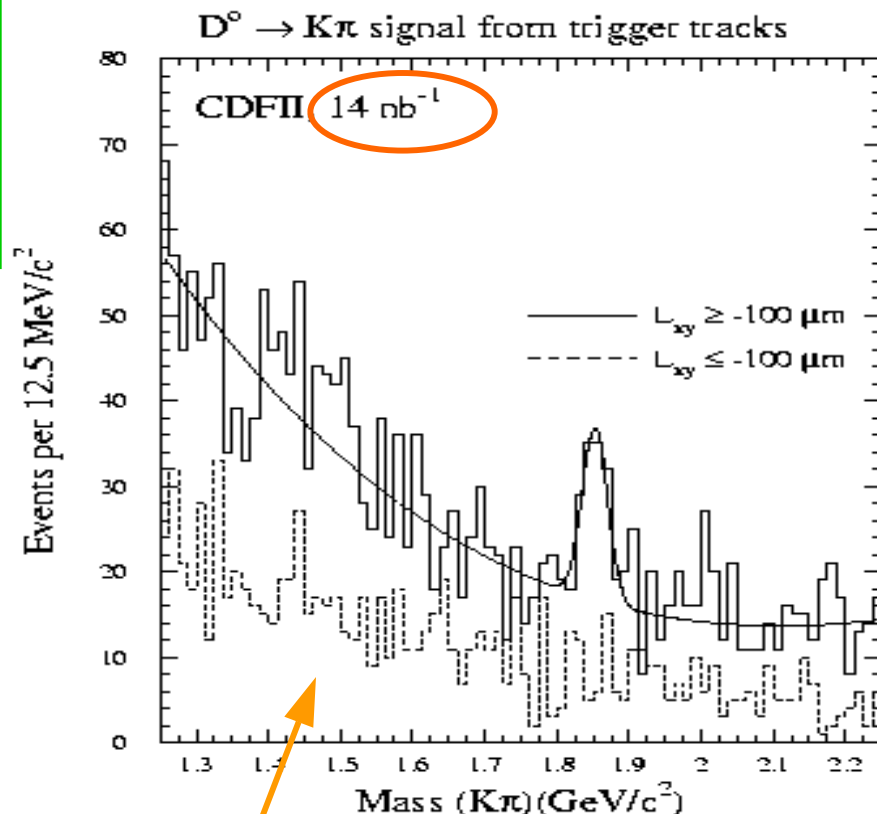
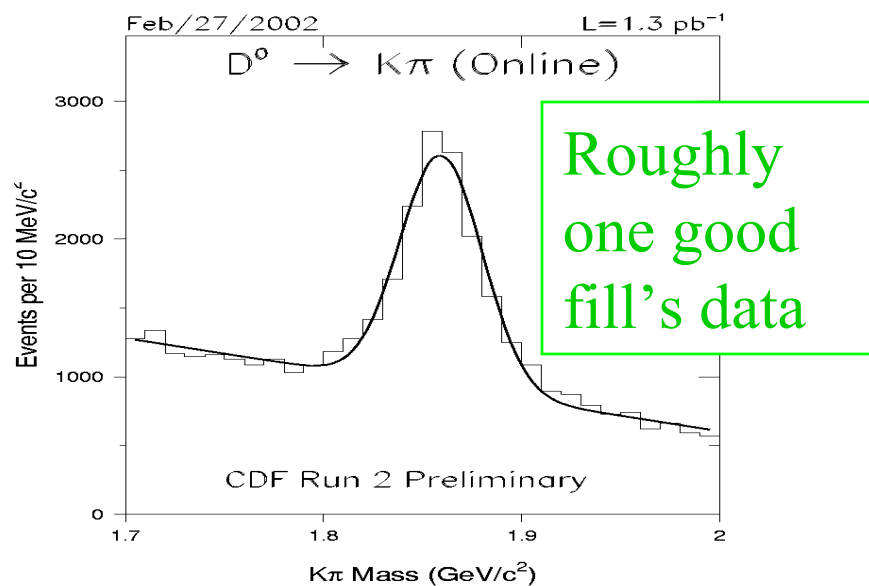
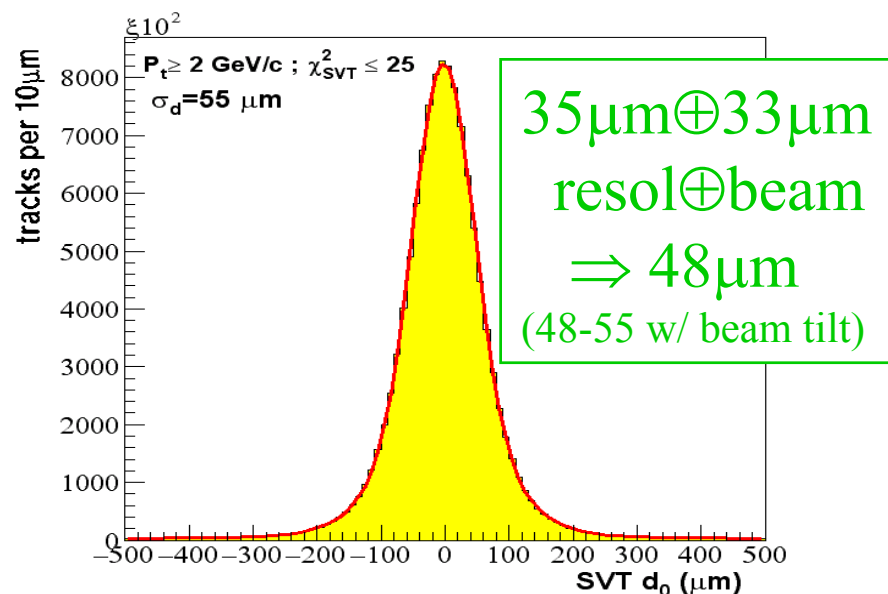
13 μ s
First hit to last track

Mission accomplished!

24 μ s
Level 1 accept
to SVT done



Et voila!



October 2001 test runs
 (~3 minutes at design luminosity)

By the way

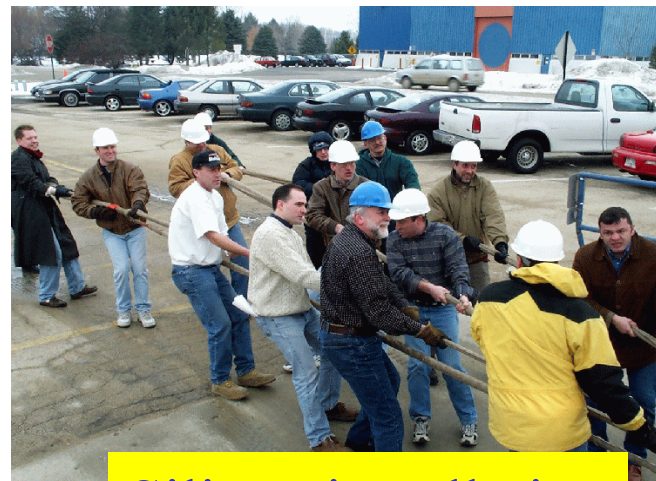
Several other design features (of technical interest) have contributed to SVT's testing and reliable operation. If you're curious, ask me about them later.

Onward!

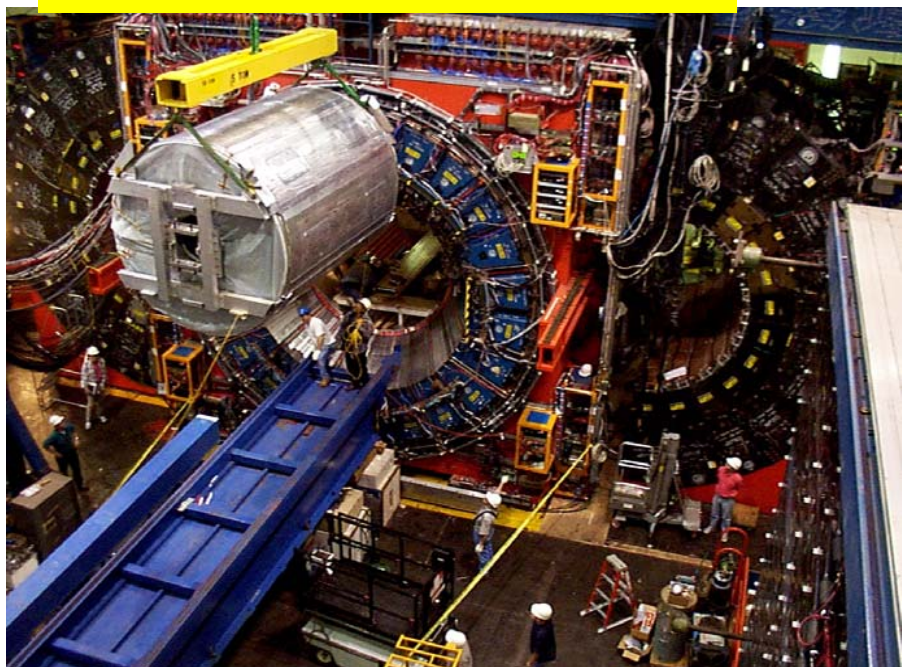
- Now that the heavy lifting is done, let's see what we can do with this device ...



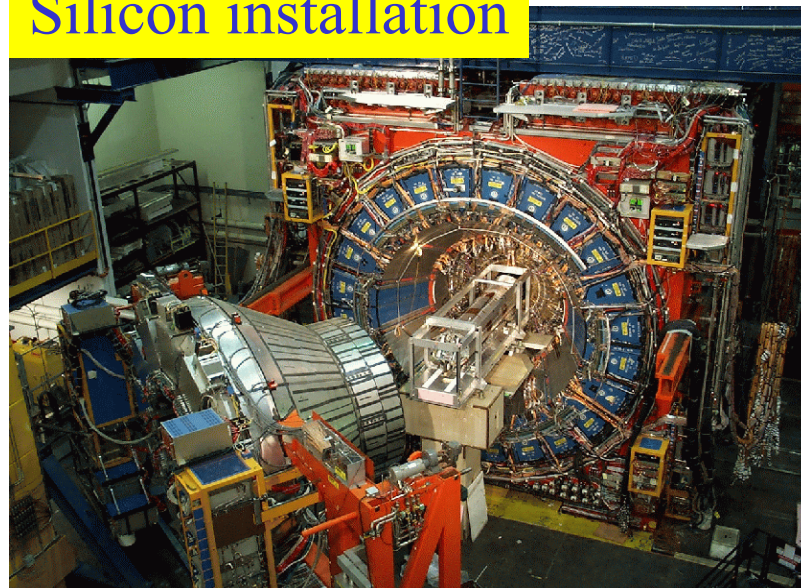
Drift chamber installation



Silicon installation



2003-03-11



Bill Ashmanskas, U. Chicago

First year's SVT physics results

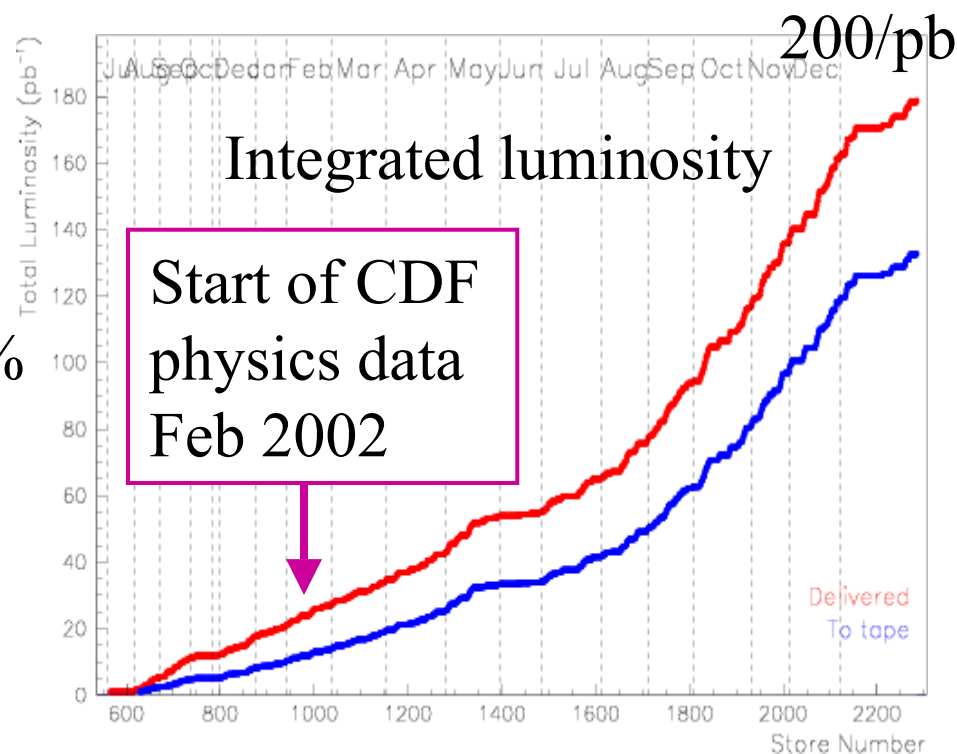
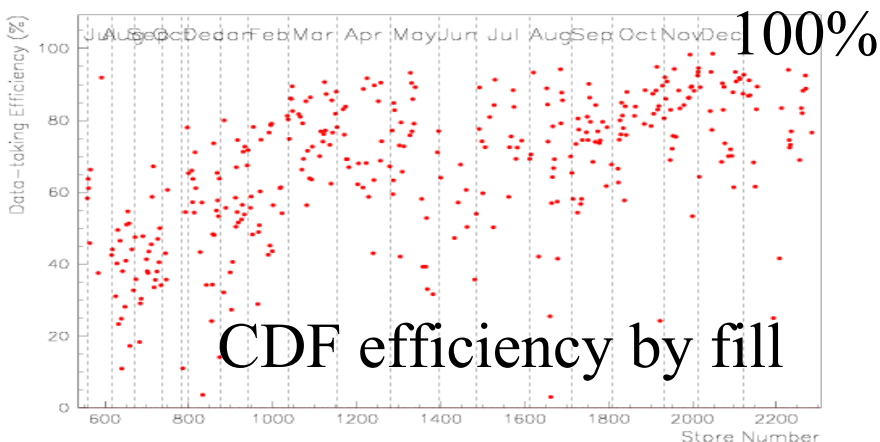
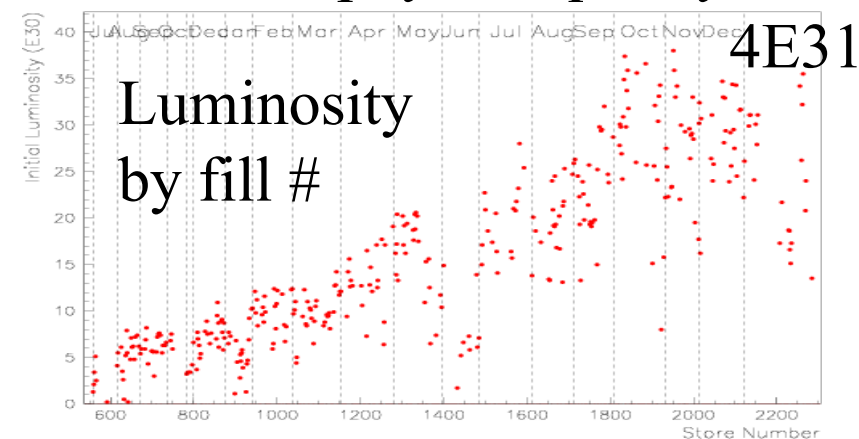
- Charm cross-section
- $\text{BR}(D^0 \rightarrow KK/\pi\pi/K\pi)$
- Rare charm decays
 - Using the “hadronic B trigger” to look for a leptonic charm decay!
- $\Delta M(D_s, D^+)$
 - first run 2 paper!!
- Warm-up to begin B physics program, e.g.
 - Find Λ_B using 0, 1, or 2 leptons in trigger
- Multi-body B_s reconstruction \rightarrow look for B_s mixing
- Two-body B_d, B_s reconstruction \rightarrow study CP asymmetries

Now is the winter of our discontent made
glorious summer by this sum of quarks

Luminosity

Making steady progress; still $\sim x2$ below goal

- Record: $3.7 \times 10^{31} \text{cm}^{-2}\text{s}^{-1}$ (run 2) vs 2.5×10^{31} (run 1)
- Best week: 7pb^{-1}
- CDF physics-quality data: $80/\text{pb}$; with silicon: $65/\text{pb}$



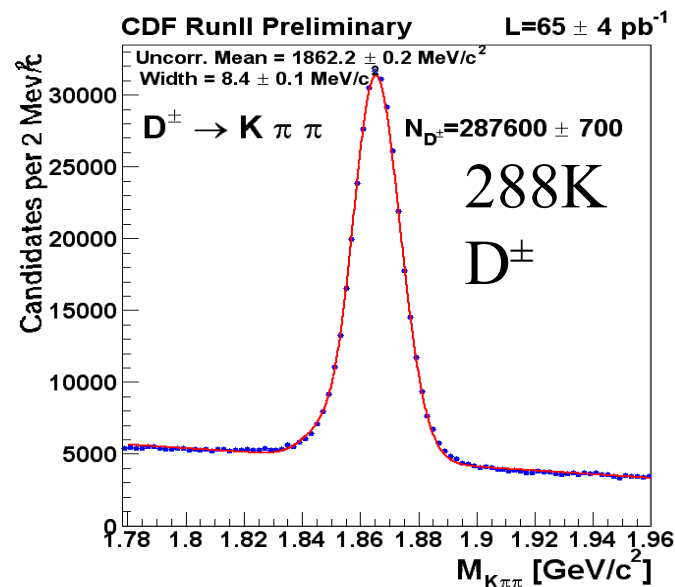
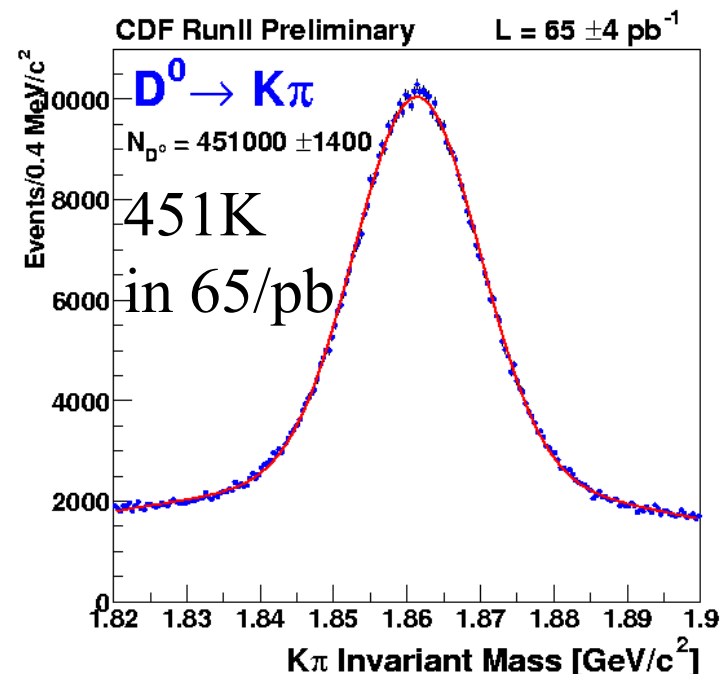
CDF's hot topic for 2002 (though you won't find it in our TDR)

Will have $O(10^7)$ fully reconstructed decays in 2/fb data set

➤ FOCUS = today's standard for huge:
139K $D^0 \rightarrow K^- \pi^+$, 110K $D^+ \rightarrow K^- \pi^+ \pi^+$

➤ A substantial fraction comes from b decays (next slide)

Some are born to discover J/ψ ,
some achieve photoproduction of charm,
and some have charm physics thrust upon 'em



D meson cross-sections

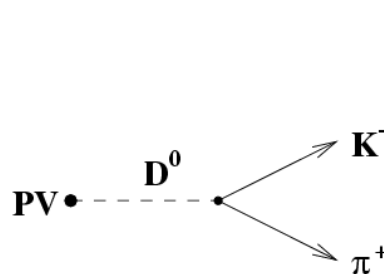
C. Chen, R. Oldeman, J. Kroll

D mesons: prompt fraction

■ D^0 :	$86.5 \pm 0.4 \pm 3.5 \%$
■ D^{*+} :	$88.1 \pm 1.1 \pm 3.9 \%$
■ D^+ :	$89.1 \pm 0.4 \pm 2.8 \%$
■ D_s^+ :	$76.0 \pm 2.7 \pm 2.1 \%$

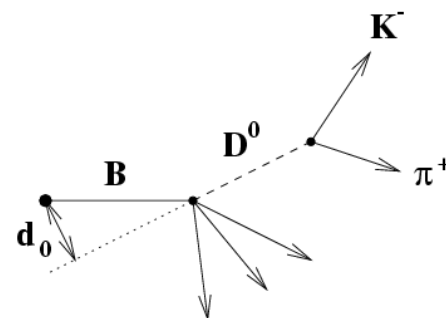
Direct Production

D points back to PV

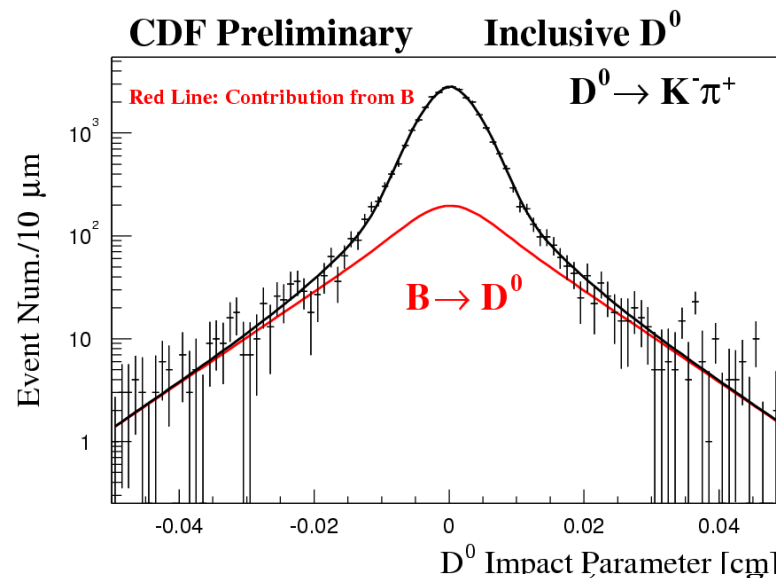
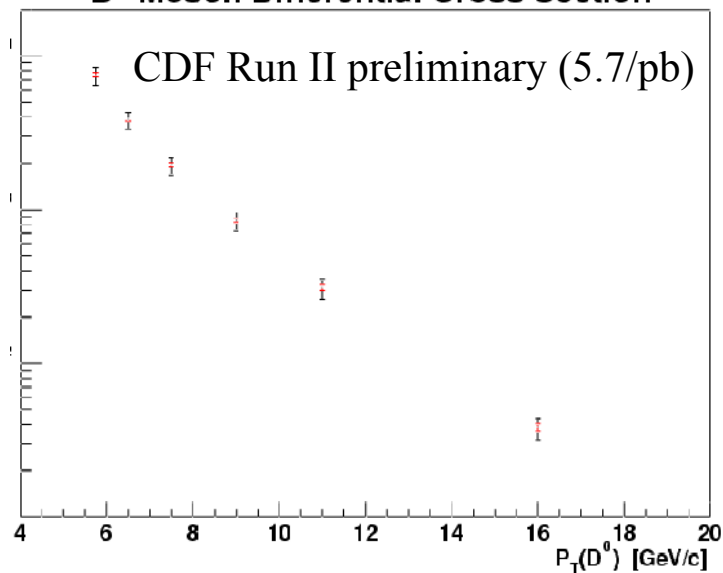


Secondary Production

D has finite impact parameter



D^0 Meson Differential Cross Section

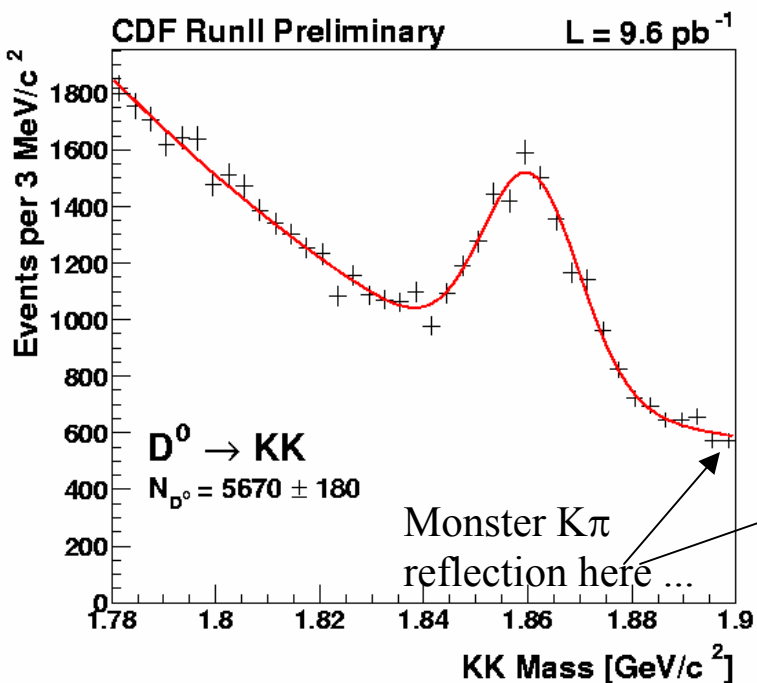


Measure Cabibbo-suppressed decay rates

CDF Rome group

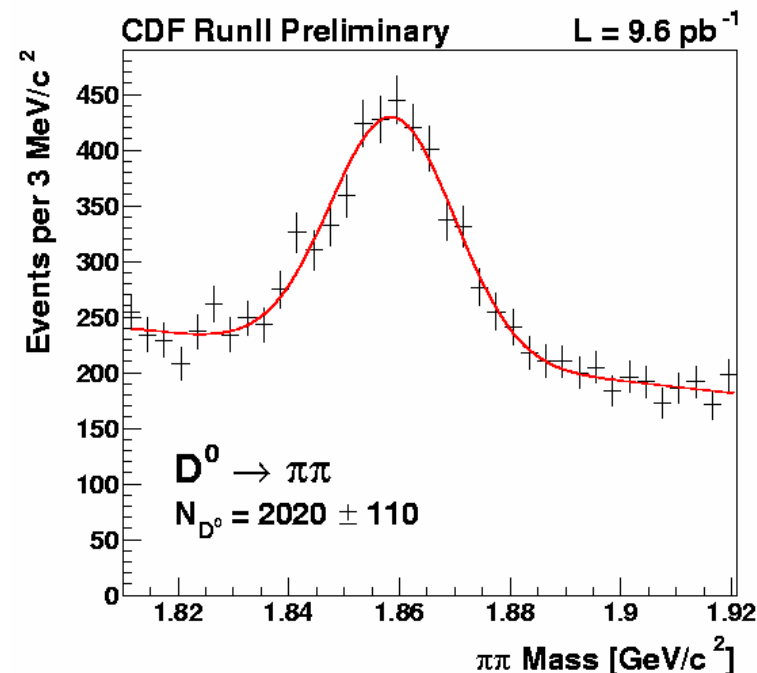
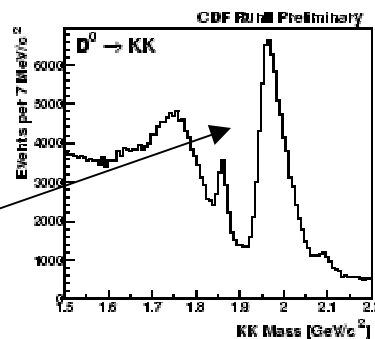
- $\Gamma(D \rightarrow KK)/\Gamma(D \rightarrow K\pi) = (11.17 \pm 0.48 \pm 0.98)\%$ (PDG: 10.83 ± 0.27)
 - Main systematic (8%): background subtraction (E687, E791, CLEO2)
- $\Gamma(D \rightarrow \pi\pi)/\Gamma(D \rightarrow K\pi) = (3.37 \pm 0.20 \pm 0.16)\%$ (PDG: 3.76 ± 0.17)
 - several $\sim 2\%$ systematics
- This measurement has pushed the state of the art on modeling SVT sculpting--essential simulation tools for both B physics program and e.g. high- p_T b-jet triggers

Already comparable



Future?

- CP violation
- mixing
- rare decays

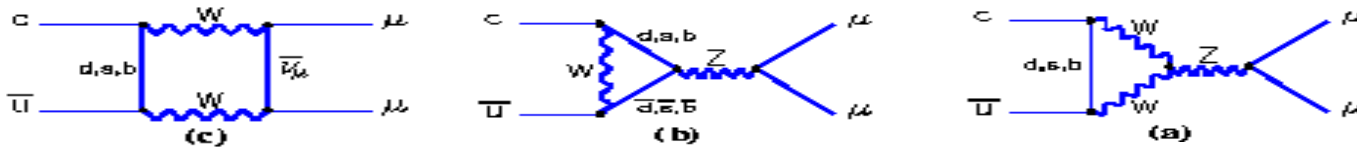


$D^0 \rightarrow \mu\mu$

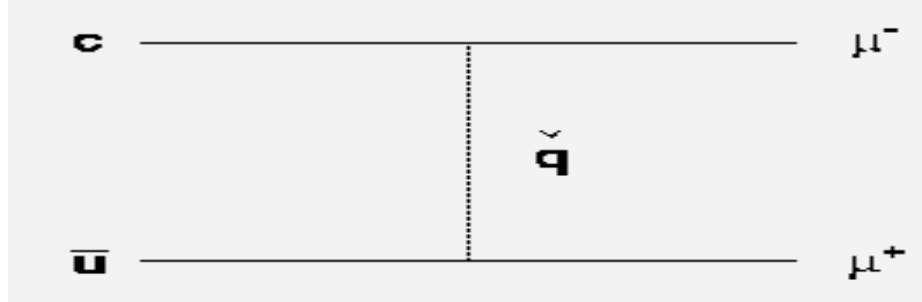
B.A., Rob Harr

$D^0 \rightarrow \mu\mu$ is an FCNC decay, GIM suppressed in the SM

- $B(D^0 \rightarrow \mu\mu) \approx 3 \times 10^{-13}$ in Standard Model



- but can be as large as 3.5×10^{-6} in some RPV SUSY models



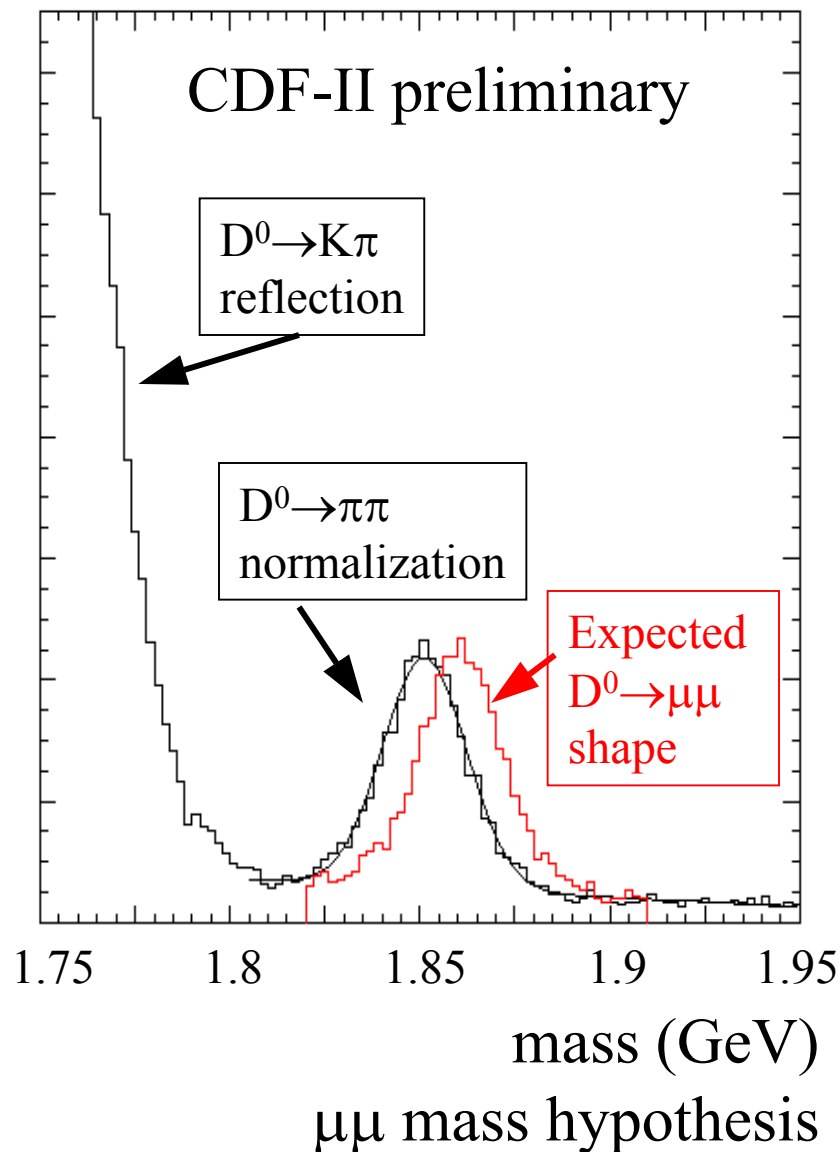
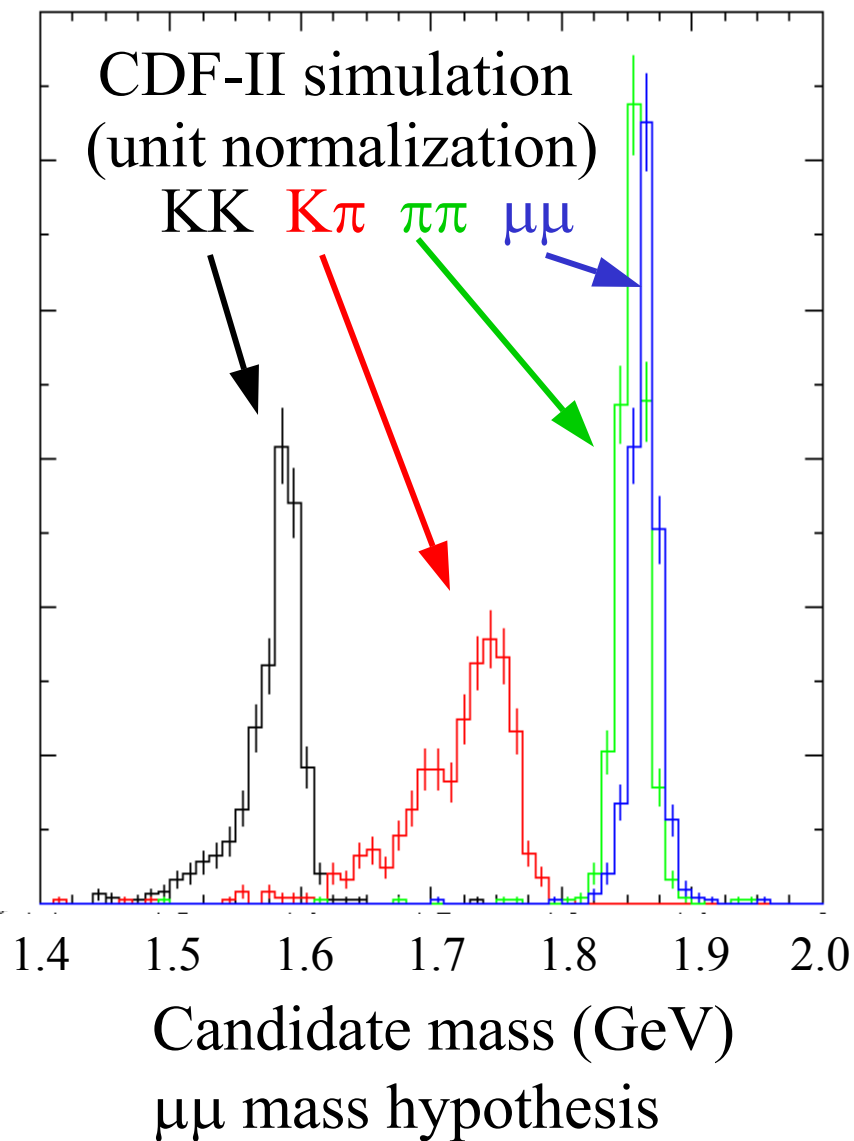
- Best limit (BEATRICE) is 4.1×10^{-6} @ 90% CL.
- We think we can do as sensitive a search with data in hand. (Maybe better--depends on how well we understand BG.)
- Haven't yet "opened the box." First results expected soon.

Analysis strategy

Use the same (displaced-track) trigger to record $\mu\mu$ signal, $\pi\pi$ normalization sample, and $K\pi$ sample for background studies

- $D^0 \rightarrow \mu\mu$ signal looks just like $D^0 \rightarrow \pi\pi$, except ...
 - need μ identification
 - 10 MeV ($\sim 1\sigma$) mass shift
- Ideally, BG dominated by $D^0 \rightarrow \pi\pi$ (BR $1.4E-3$), where both pions fake muons (punch-through)
- $\sim 1.4\%$ $\pi \rightarrow \mu$ fake rate
 - BG should be equivalent to BR $= 3E-7$
- still working on understanding combinatorial BG

Mass separation of decay modes



Ingredients

- Number of $D^0 \rightarrow \pi\pi$, fiducial in muon chambers
- Muon ID efficiency
- Expected background
 - doubly-mistagged $D^0 \rightarrow \pi\pi$ (need misID rate)
 - combinatorial BG (a few real muons possible?)
- Number of signal events, or an upper limit, based on observed number of events

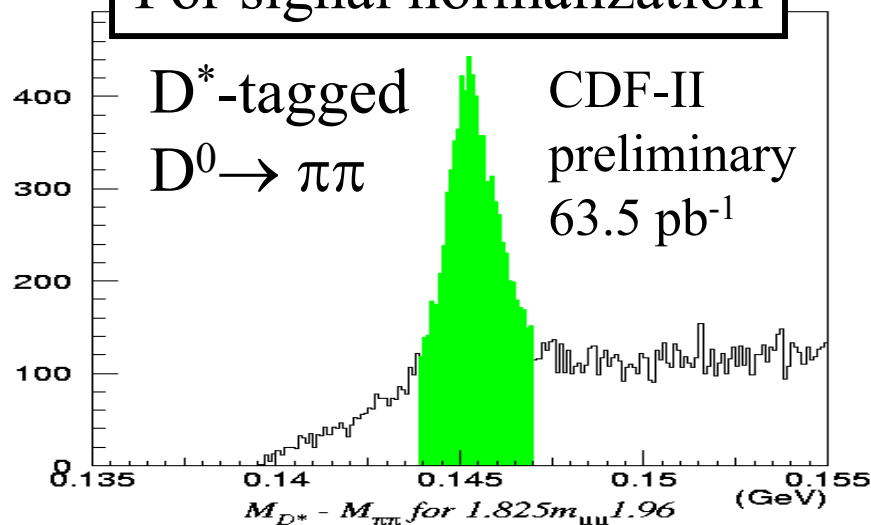
$$B(D^0 \rightarrow \mu\mu) = B(D^0 \rightarrow \pi\pi) \times \frac{N(D^0 \rightarrow \mu\mu)}{N(D^0 \rightarrow \pi\pi)} \times \frac{\epsilon(D^0 \rightarrow \pi\pi)}{\epsilon(D^0 \rightarrow \mu\mu)},$$

or in the case of an upper limit,

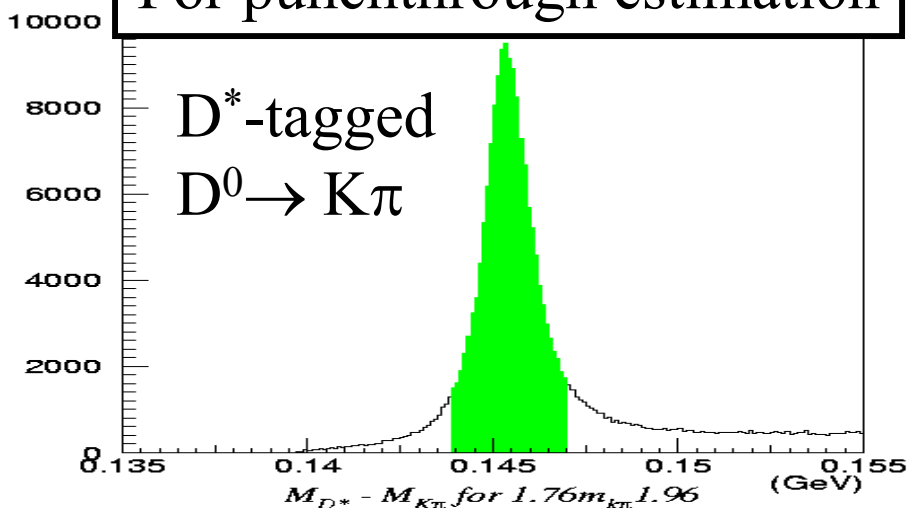
$$B_{90\%CL}(D^0 \rightarrow \mu\mu) = B(D^0 \rightarrow \pi\pi) \times \frac{N_{90\%CL}^{upper}}{N(D^0 \rightarrow \pi\pi)} \times \frac{\epsilon(D^0 \rightarrow \pi\pi)}{\epsilon(D^0 \rightarrow \mu\mu)}.$$

$D^0 \rightarrow \pi\pi, K\pi$ reference signals

For signal normalization

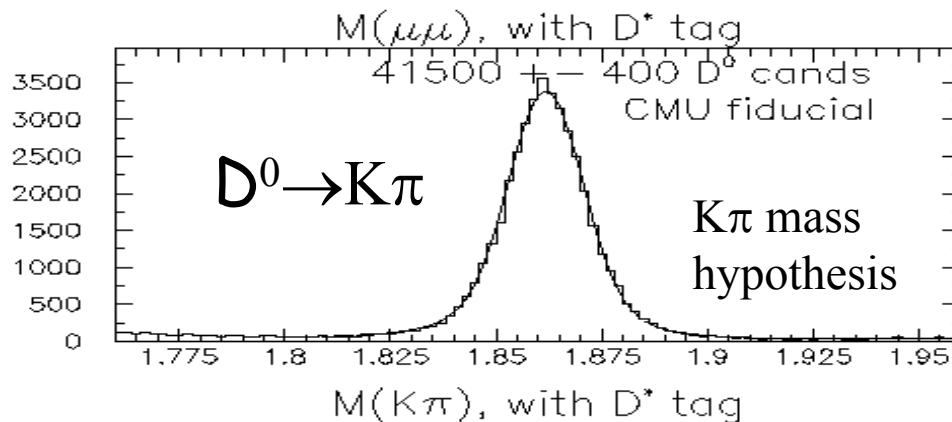
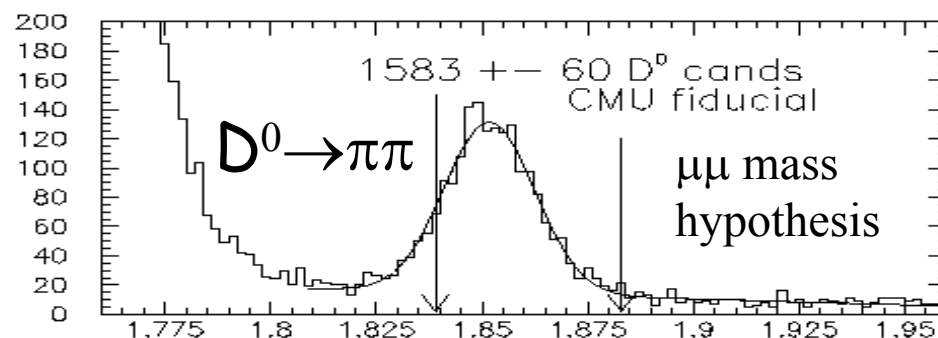


For punchthrough estimation



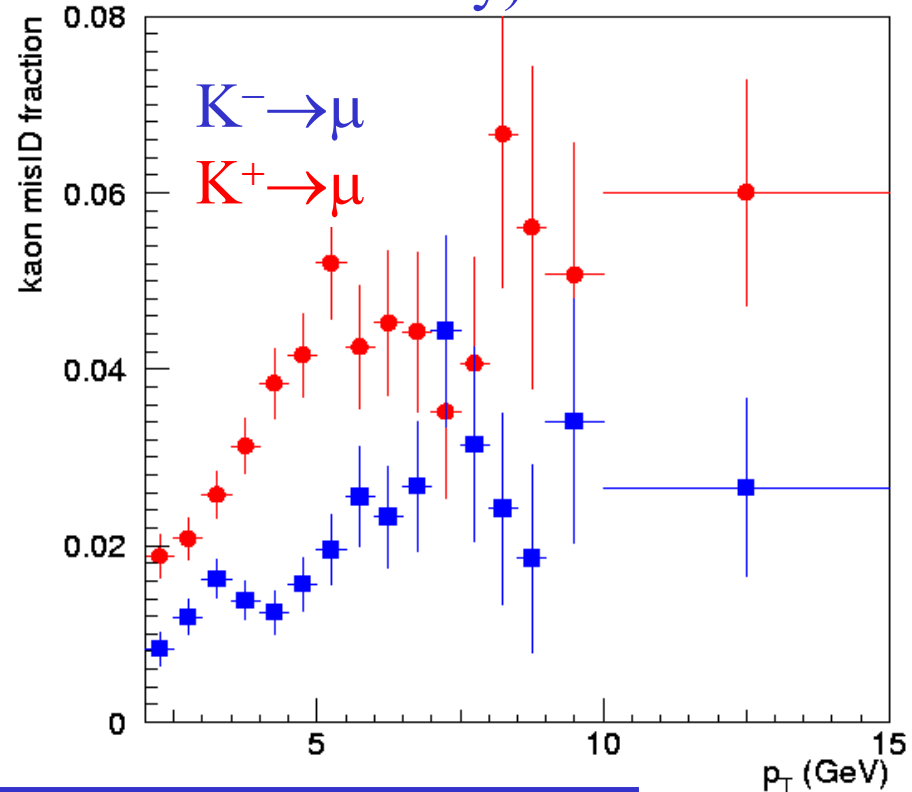
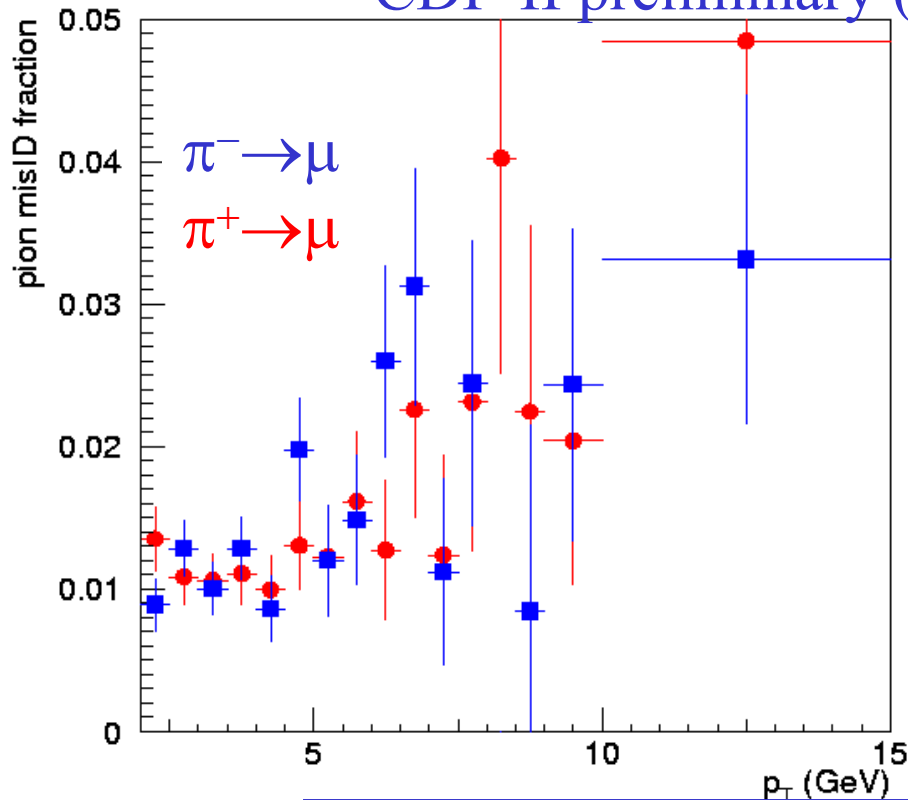
See 4345 \pm 90 D^{*-} -tagged $D^0 \rightarrow \pi\pi$

- 1583 \pm 60 after muon fiducial cuts (x0.36) (subset of muon system)
- 11MeV mass resolution
- 10MeV offset $\mu\mu - \pi\pi$



$K \rightarrow \mu, \pi \rightarrow \mu$ misidentification

CDF-II preliminary (statistical errors only)



Estimate punchthrough using D^* -tagged $D^0 \rightarrow K\pi$

Average $\pi \rightarrow \mu$ fake rate (folding in track spectrum) is $\sim 1.4\%$ ($\sim 2.4\%$ for $K \rightarrow \mu$).

Expect (naively) $1583 \times 0.84 \times 0.014 \times 2 = 0.3$ $D^0 \rightarrow \pi\pi$ BG events

➤ 0.84 comes from 1σ shift of 2σ window

Sensitivity (closed box)

After some cut optimization, we fit 1429 ± 56 events in normalization mode

- 1374 ± 82 events after relative efficiency

If no event, 90%CL limit would be roughly

- $1.4\text{E-}3 * 2.3 / 1374 = 2.3\text{E-}6$

Future directions:

- Accumulate data, understand BG sources, hopefully reach well below $\text{E-}6$
- Analysis partner (Rob) wants to do $\pi\mu\mu$
- I'd like to do $e\mu$, ee

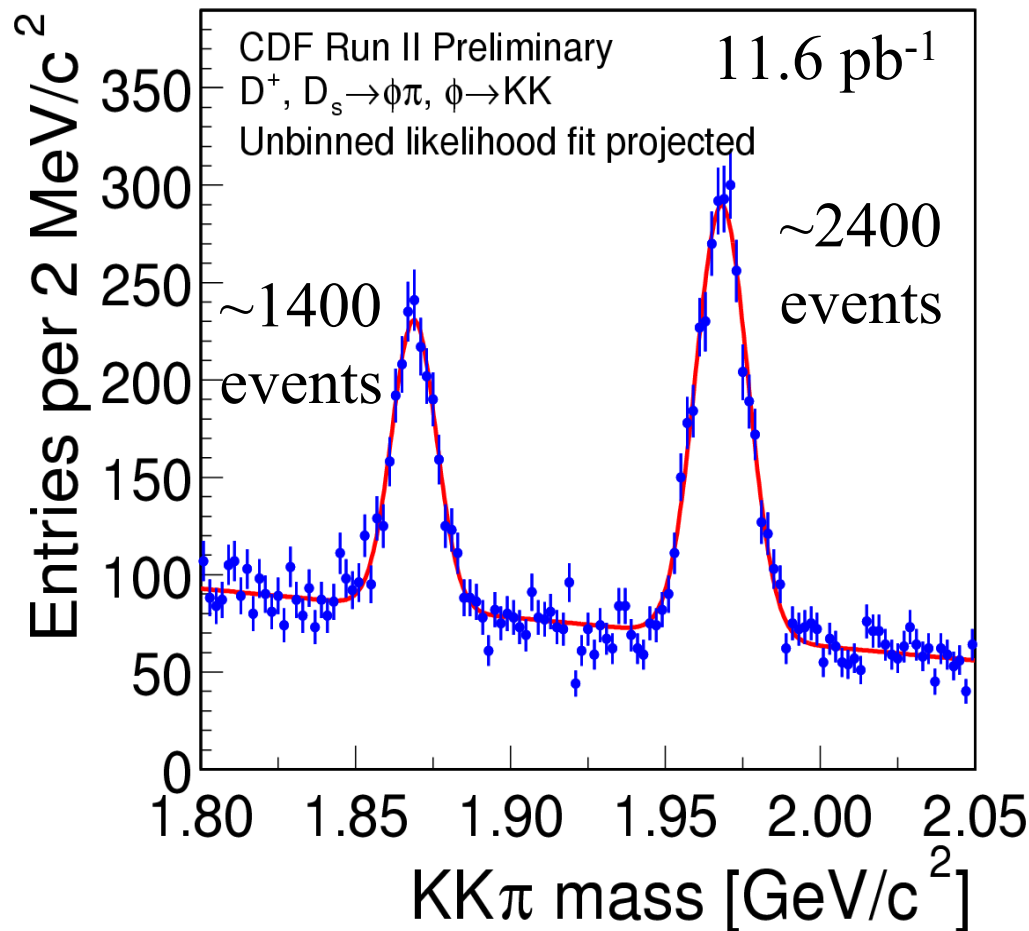
Measure D_s , D^+ mass difference

Ivan Furic

$D_s^\pm - D^\pm$ mass difference

- Both $D \rightarrow \phi\pi$ ($\phi \rightarrow KK$)
- $\Delta m = 99.41 \pm 0.38 \pm 0.21$ MeV
- PDG: 99.2 ± 0.5 MeV
(CLEO2, E691)
- Systematics dominated by background modeling

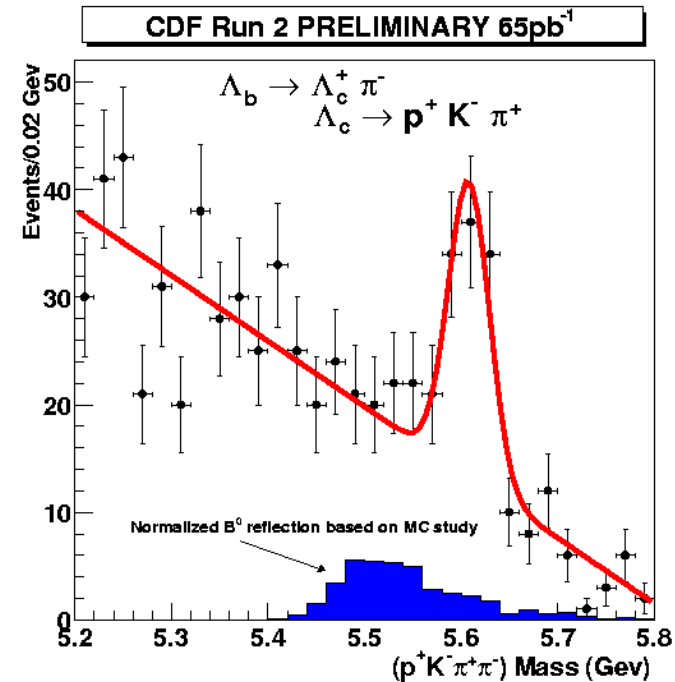
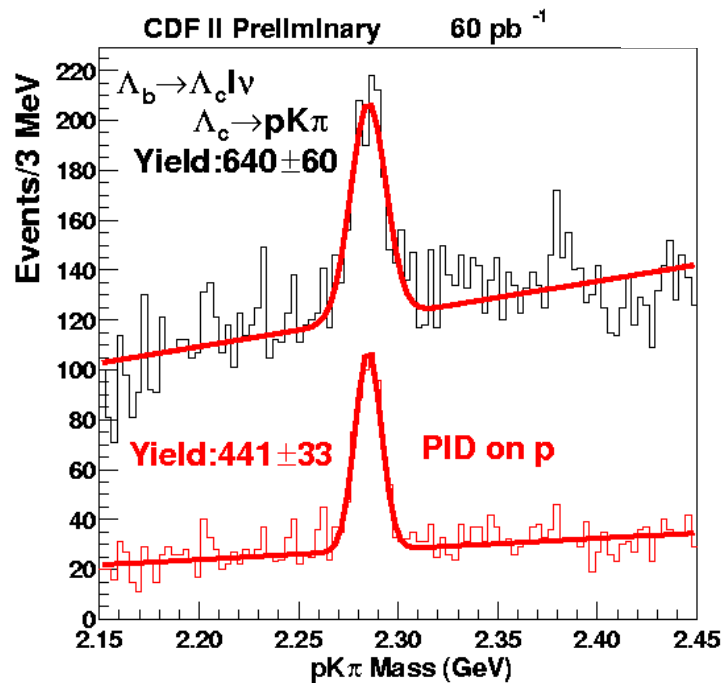
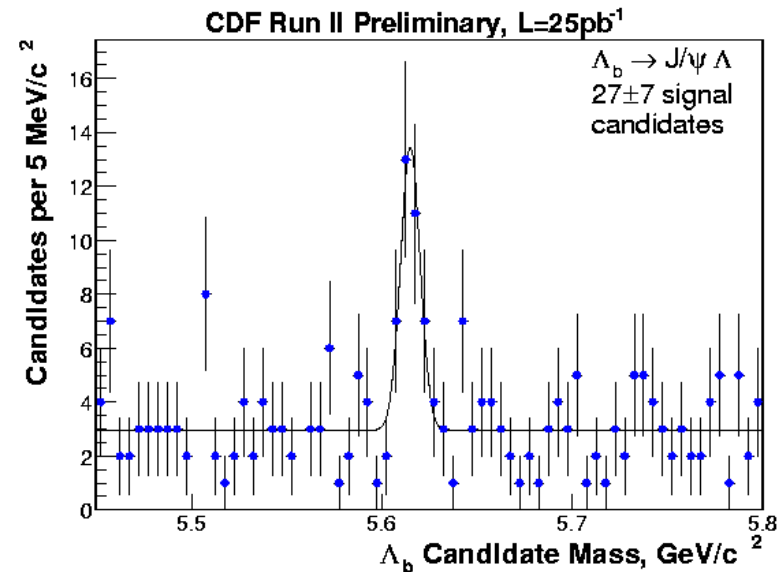
Made possible by new trigger capabilities, even as Run 2 is just getting started.



Getting the B physics program warmed up

Starting to see nice B signals
(with 0, 1, or 2 leptons)

BR's are lower for B than D, so
it takes a bit longer to get going



Bs flavor oscillations: a CDF goal for 2004

Strong interaction produces a B s or a \bar{B} s state at $\tau = 0$.

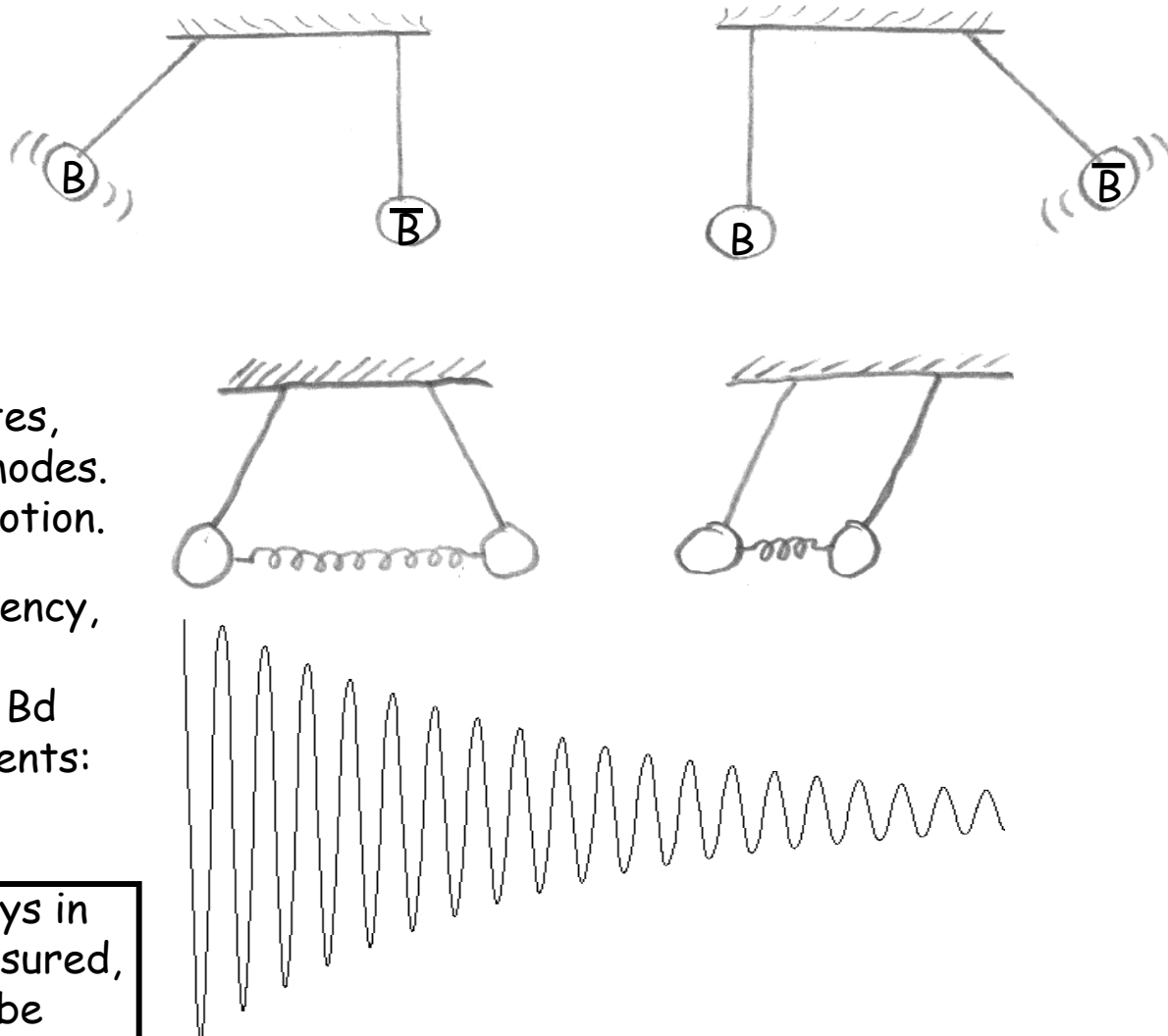
B s states are not produced at the b factories

Weak interaction couples states, splits frequencies of normal modes. Weak decay also damps the motion.

Goal: measure the beat frequency, and hence the state splitting.

Ratio of splittings for B s and B d relates two CKM matrix elements:
 $\Delta M_s / \Delta M_d \sim |V_{ts}|^2 / |V_{td}|^2$

SVT selects a sample of decays in which proper time is well measured, so that many oscillations can be resolved. (Neutrinoless final state.)



Mixing in a nutshell

If

$$|\psi(t=0)\rangle = |B_S\rangle$$

then

$$\langle B_S | \psi(t) \rangle = \frac{1}{2\tau} (1 + \cos(\Delta m t)) e^{-t/\tau}$$

$$\langle \overline{B}_S | \psi(t) \rangle = \frac{1}{2\tau} (1 - \cos(\Delta m t)) e^{-t/\tau}$$

Need to know:

- Proper decay time = $L/\gamma\beta = L \cdot \frac{m_B}{p_B}$
- B_S vs \overline{B}_S at decay
- B_S vs \overline{B}_S at $t = 0$ (“flavor tagging”)

Imperfect tagging:

- “dilution” $D = \frac{R-W}{R+W}$
- $1 \pm \cos(\Delta m t) \rightarrow 1 \pm D \cos(\Delta m t)$

Define $x = \Delta m/\Gamma$

$$\text{Sig}(x) = e^{-\frac{1}{2}(x\sigma_t/\tau)^2} \sqrt{\frac{N\epsilon D^2}{2}} \sqrt{\frac{S}{S+B}}$$

So important ingredients are:

- Event yield
- Clean signals (S/B)
- Vertexing resolution
- Effective tagging efficiency: ϵD^2

$B_s \rightarrow D_s^- \pi^+ : \epsilon D^2$	
Same-Side Kaon	4.2%
μ tag	1.0%
e tag	0.7%
Jet Charge	3.0%
Opp.-Side Kaon	2.4%
Total (correl. small)	11.3%

(some year ~2000 projections)

Proper time resolution: two components

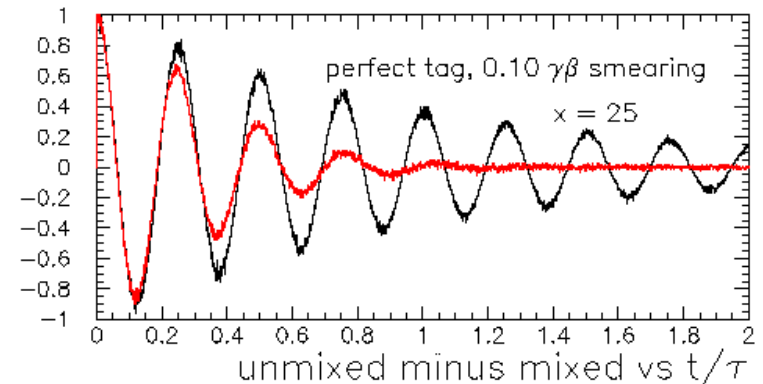
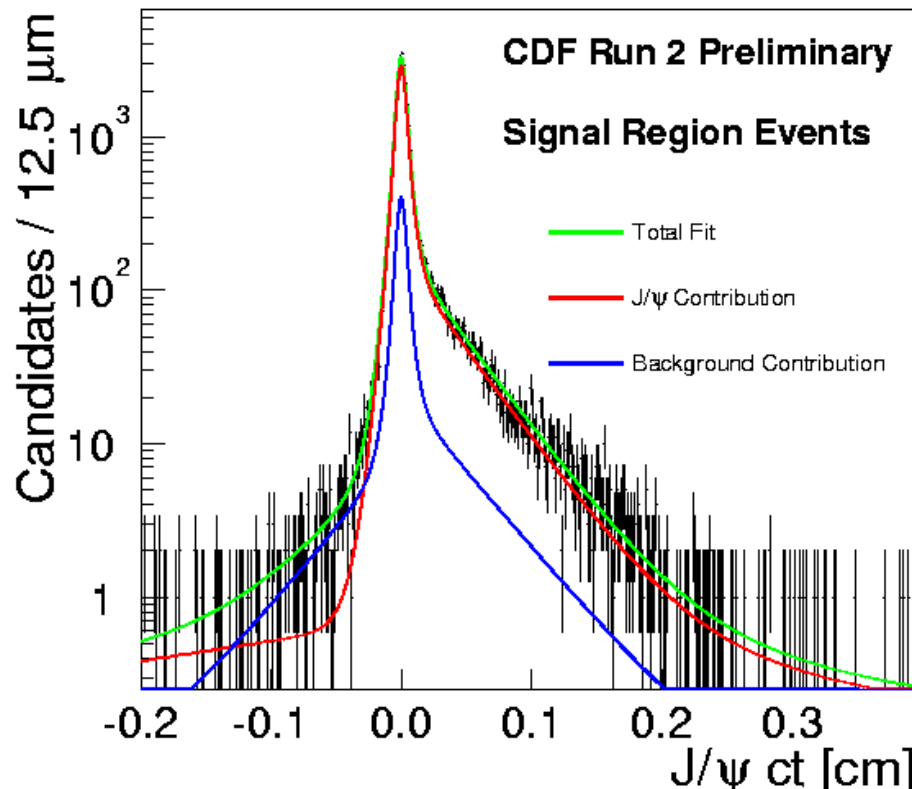
- Vertex resolution is on track
 - making lifetime measurements
- Using fully reconstructed decays is key to boost resolution

$$c\tau = \frac{L}{\gamma\beta}$$

$$\sigma_{c\tau} = \left(\frac{\sigma_L}{\gamma\beta} \right) \oplus \left(\frac{\sigma_{\gamma\beta}}{\gamma\beta} \right) \cdot c\tau$$

$\approx \text{constant}$

multiplicative error
 $\sim 15\%$ (semileptonic)
 $\sim 0.5\%$ (hadronic)

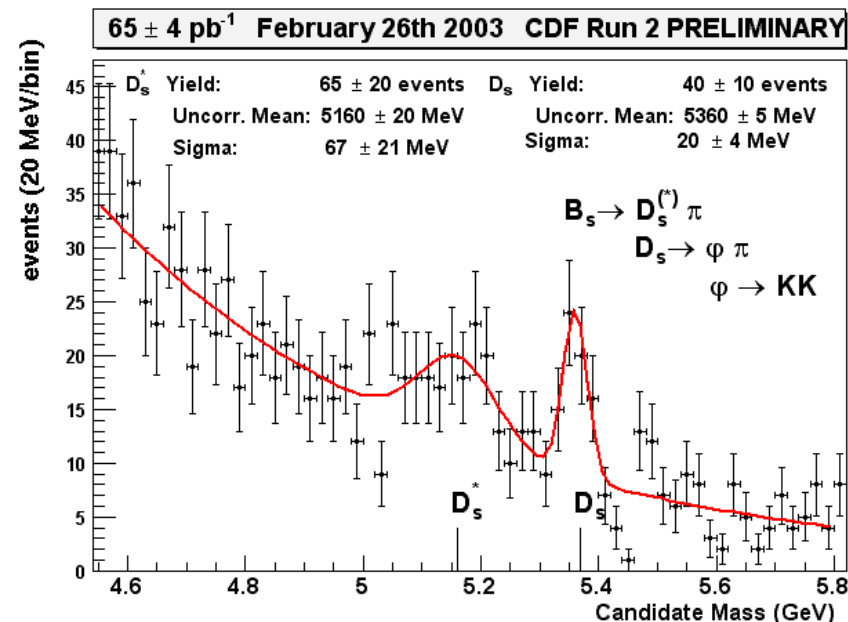
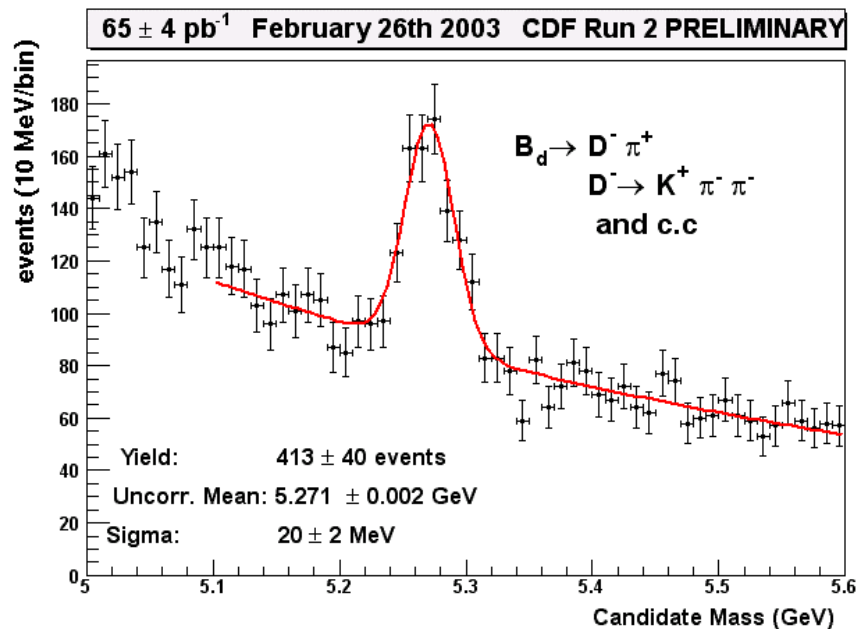
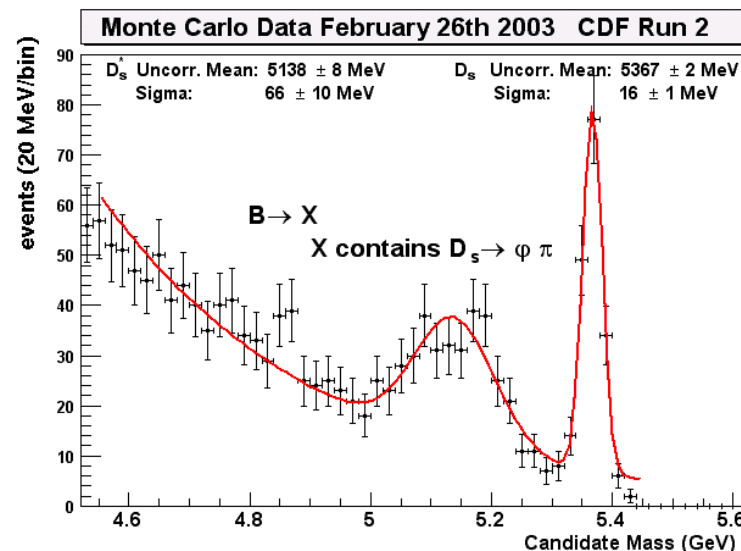


Toward B_s mixing: reconstructing fully hadronic B decays

Start with a couple of channels

- so far so good
- MC models the shape!!
- Studies of additional decay modes in progress

Donatella Lucchesi

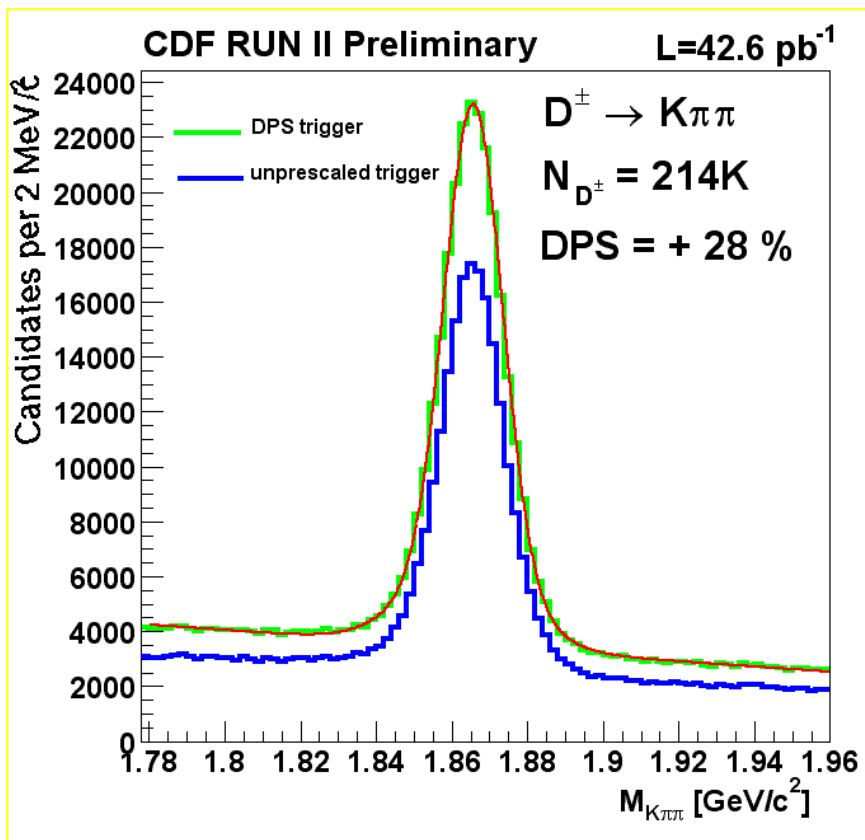


Mixing prospects

We still have a good chance to see x_s , if we boost event yields:

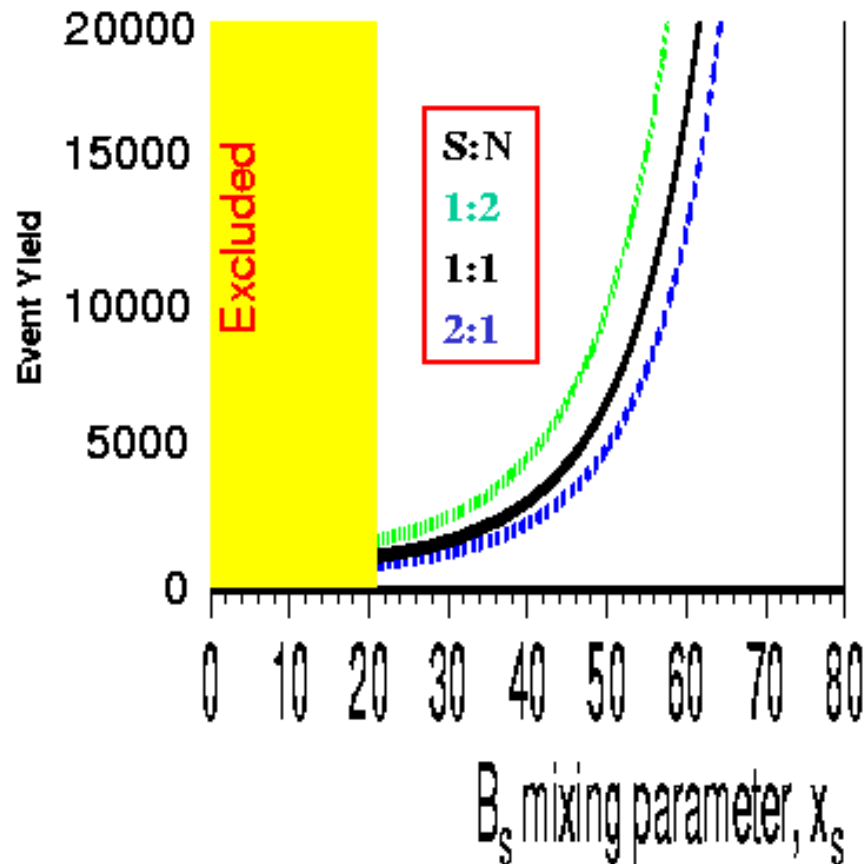
- More decay channels
- Make even better use of DAQ bandwidth

$$\text{Sig}(x) = e^{-\frac{1}{2}(x\sigma_t/\tau)^2} \sqrt{\frac{N\epsilon D^2}{2}} \sqrt{\frac{S}{S+B}}$$



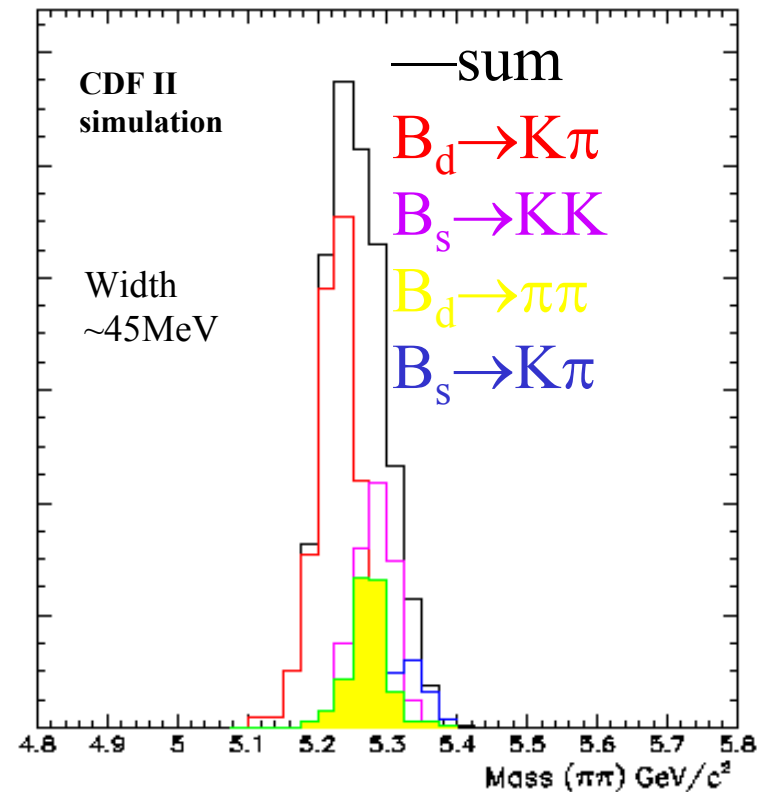
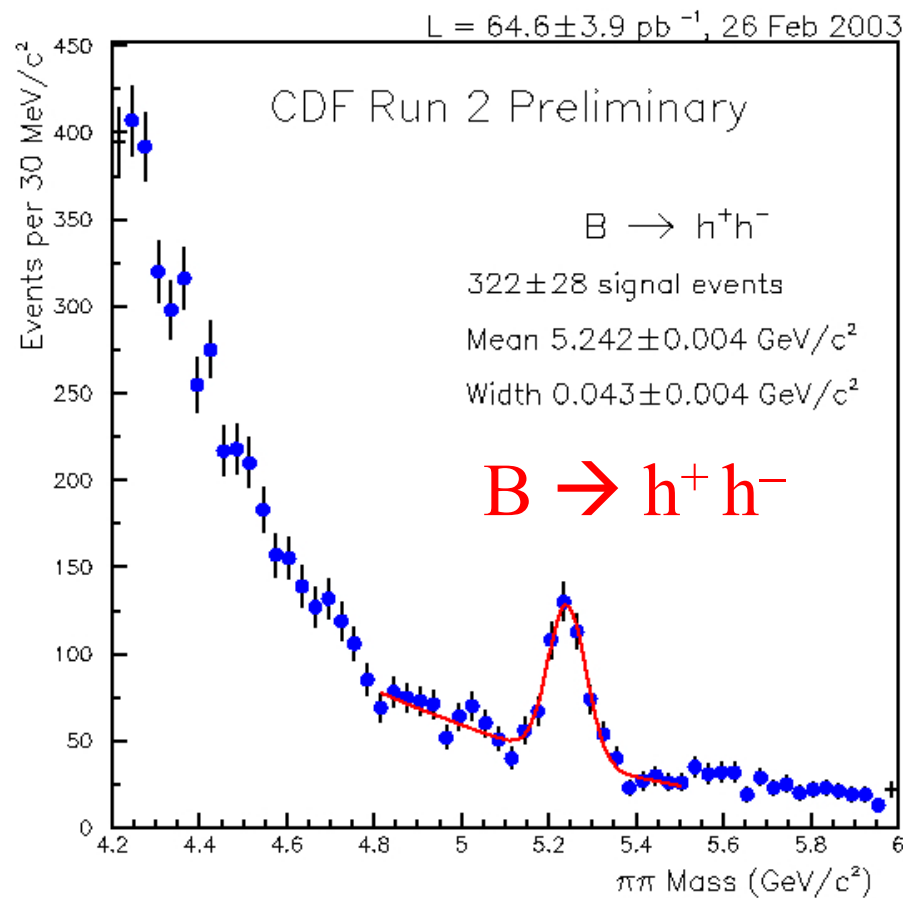
2003-03-11

Mixing 5 σ Discovery Sensitivity



Bill Ashmanskas, U. Chicago

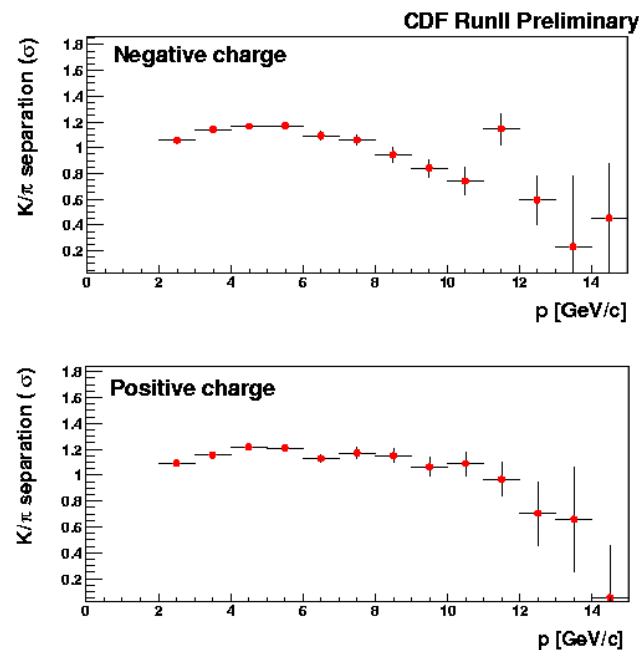
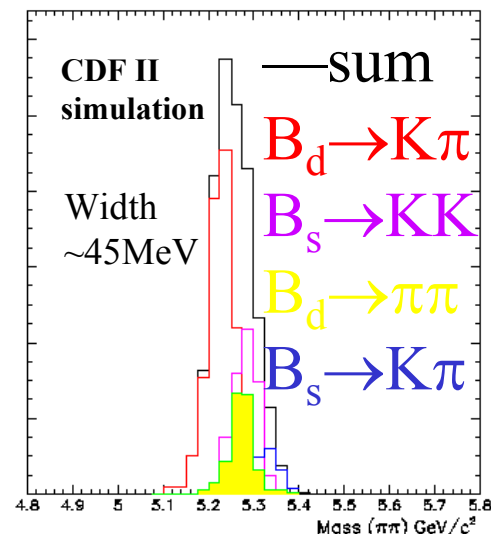
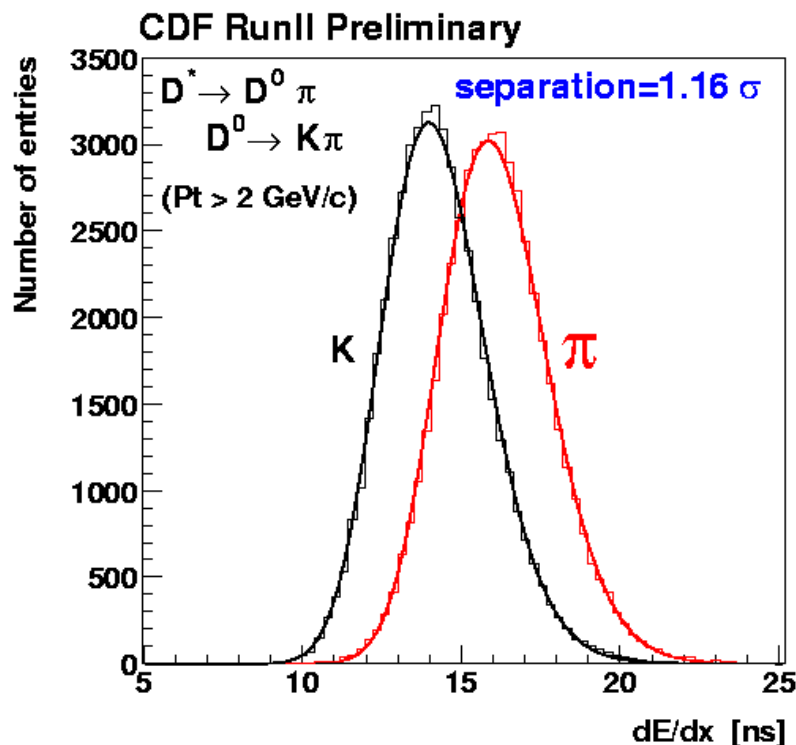
2-body hadronic B decays observed



➤ Yield as expected from detailed simulation

$B \rightarrow h^+ h^-$: next steps

- Use mass, dE/dx to separate
- Soon: measure B_s fraction
- Next: direct CPV in $B^0 \rightarrow K^+ \pi^-$
 - estimate $\sigma \sim \text{binomial} \times 1.5$
- Later: with 2 fb^{-1} sample, measuring γ to $\sim 5\text{-}10^\circ$ may be feasible (Fleischer)



Summary

- ❖ CDF's Silicon Vertex Trigger is a significant step forward in technology for hadron collider physics
- ❖ SVT has a big impact on CDF's Run 2 physics program
- ❖ Trigger capabilities allow us to make good use of a wide range of instantaneous luminosities

- ❖ As many fully reconstructed D^0/pb^{-1} at CDF as D^0/fb^{-1} at BF!
 - Surprise!
- ❖ $\text{BR}(D^0 \rightarrow \text{KK}) / \text{BR}(D^0 \rightarrow \text{K}\pi)$,
 $\text{BR}(D^0 \rightarrow \pi\pi) / \text{BR}(D^0 \rightarrow \text{K}\pi)$
 - next: Lifetime differences?
- ❖ Rare decays: $D^0 \rightarrow \mu\mu$
 - next: $\mu\mu\pi$, $e\mu$, ee ?
- ❖ $\Delta M(D_s, D^+)$
 - first Run 2 paper!

- ❖ Next summer? B_s mixing
 - Lots of work to do to maximize event yields, optimize reconstruction, develop flavor tagging, ...
- ❖ $B^0, B_s \rightarrow h^+ h^-$
 - Use mass, dE/dx to disentangle
 - Near term: direct CPV?
 - Longer: measure γ to $5-10^\circ$?

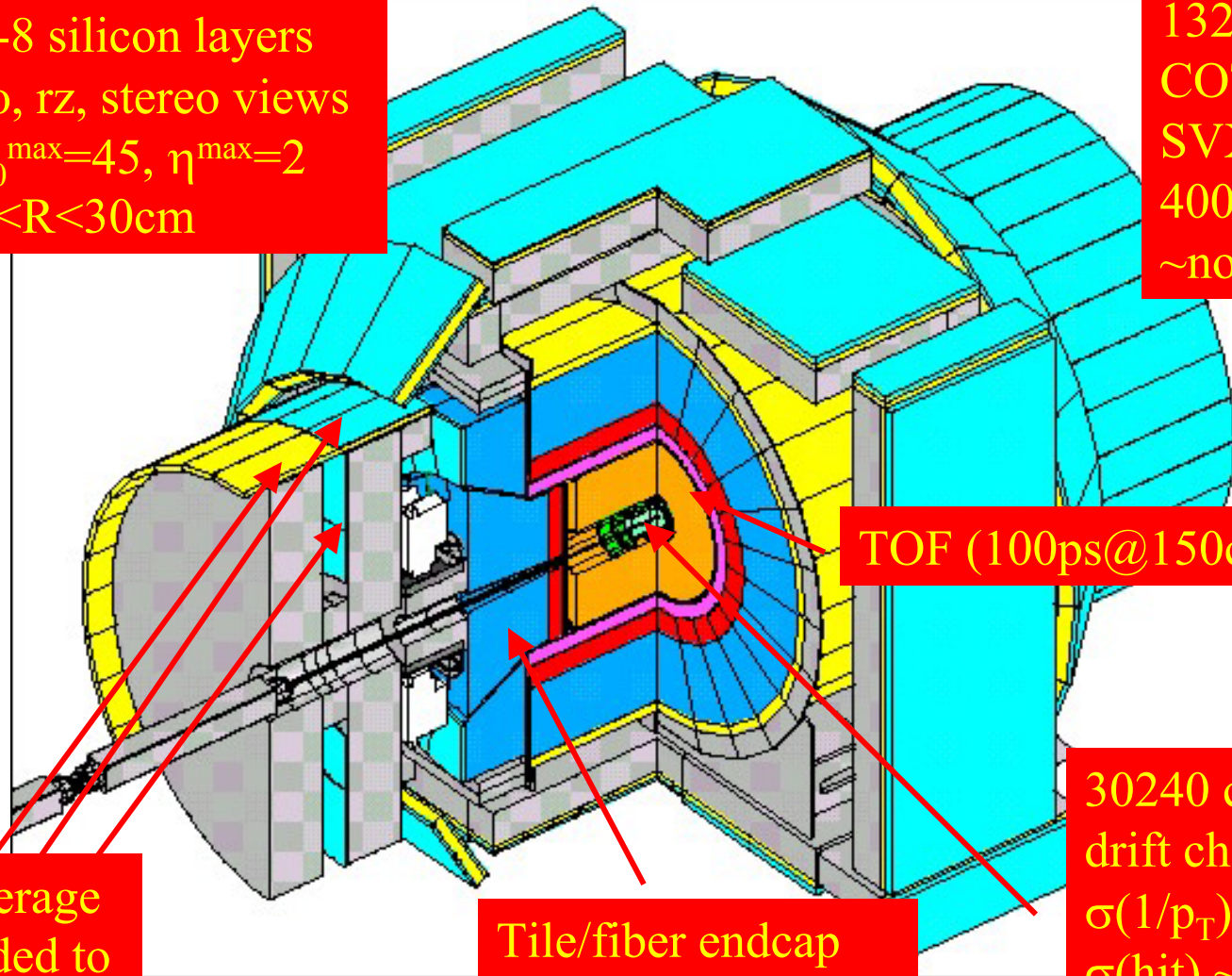
The End

Everything past this point is backup, etc.

CDF Detector Run II Upgrades

7-8 silicon layers
 $r\phi$, rz, stereo views
 $z_0^{\max}=45$, $\eta^{\max}=2$
 $2 < R < 30\text{cm}$

132 ns front end
 COT tracks @L1
 SVX tracks @L2
 40000/300/70 Hz
 ~no dead time



TOF (100ps@150cm)

μ coverage
 extended to
 $\eta=1.5$

Tile/fiber endcap
 calorimeter (faster,
 larger F_{samp} , no gap)

30240 chnl, 96 layer
 drift chamber
 $\sigma(1/p_T) \sim 0.1\%/GeV$
 $\sigma(\text{hit}) \sim 150\mu\text{m}$

Hadron Collider Jargon

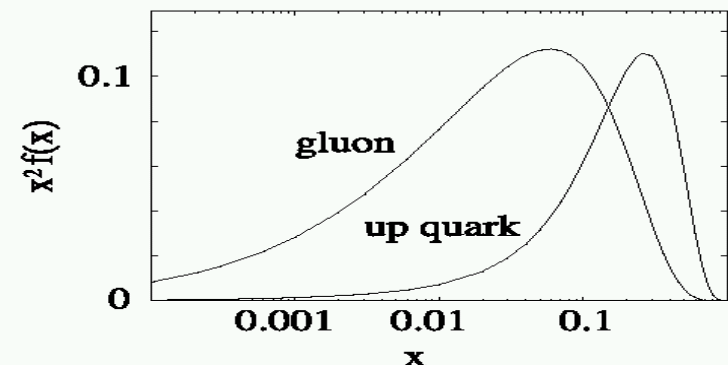
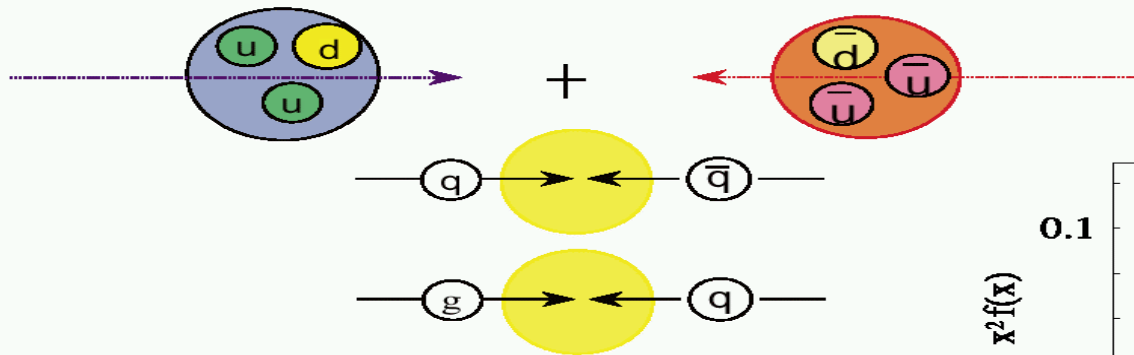
Really colliding partons: qg , qq , gg

- q can be a valence (u, d) or sea quark (\dots, s, c, b, \dots)

Momenta given by Parton Distribution Functions (PDF's)

- $p_t \equiv$ transverse momentum must balance
- $p_z \equiv$ longitudinal momentum (along the beam) unknown
- Coordinates (r, ϕ, θ) with $\eta = \text{arctanh}(\cos(\theta))$ (pseudorapidity)
- Distributions $dN/d\eta$ invariant under boosts in z

Broadband: Production of particle states with cm energies from a few up to 100's of GeV



The CDF Silicon Vertex Trigger

- innovative : new window onto b,c physics at CDF
- motivation, techniques, first year's physics results

Why a hadronic B trigger at CDF?

- "Let's start with the why's"
- This question has 4 parts, which I'll address in turn.
- (Quickly on this one; there's no content.)

Why study bottom and charm decays?

- Name of the game is to map out CKM
- See if single CKM phase describe all of the CPV we can currently study in the laboratory
- We study hadrons: symbiosis between study of strongly-coupled QCD and study of weak interactions of quarks
- Beyond studying CKM, we use tools of B physics to search for new physics ...

Why at CDF?

- Don't read all the "down side" stuff; just note that one can't fully reconstruct the event back to the hard scattering process ... and the luminous region is a meter long ... and we know neither its CM energy nor its rapidity.
- Nevertheless, we do have handles to identify B decays at CDF (next slide) ...

Particle signatures at CDF

- (Oops, someone got the B field backwards)
- Point out that this is a transverse view of a caricature of CDF
- Can point to e, mu on left, and displaced vertex on right

Why do you need a trigger?

- At a hadron collider experiment, you're really looking for needles in haystacks!
- Point out that we're in the R-Z view now
- 2.5 MHz crossing rate \gg 50 Hz "tape" output rate
- tt (before BR penalty) is 10 orders down from crossing rate
- bb (central, before BR penalty) is only 4 orders of magnitude down
- when you're b/w limited, the number of signal events you can record is proportional to the rejection factor you achieve for background (assumes $S \ll B$)

A salient property of b,c decay: lifetime

- Point out that we're back in the r-phi view
- Gesture to illustrate impact parameter
- Contrast with leptonic triggers: 75% of decays inaccessible; 10-15% smearing on Lorentz boost factor \Rightarrow hard to measure time-dependent asymmetries

Division of labor: 3-step selection

- Henry really hates the construction metaphor: says the trigger does a better job than the software (oh well)
- Go through this fairly quickly; can be more specific on next slide
- 2 / 2 / 1 order magnitude rejection; different technologies for different time scales, different granularities of filtering
- having two drift chamber tracks of moderate momentum gets us up off the ground, where "min bias" events leave just a few soft tracks per unit phase space
- the drift chamber tracks provide the foundation for SVT tracking, which lives at the second level
- we have only tens of usec available, so we need techniques optimized for speed

SVT for B0 to pipi

- This was the benchmark channel for SVT design
- Point out that drift chamber tracks are given to us by L1 trigger; silicon readout is initiated upon L1 accept
- Remember, a x1000 improvement in S/B is a x1000 factor in the number of signal events you can write out
- $10^{**}5$ pb (0.1ub) is 10Hz @ E32, low enough to consider writing out
- note final S/B O(1:1)

Introducing ... SVT

- I've been at this game for 4 years; Luciano started it 12 years ago (!), before anyone had even made a silicon detector work at a hadron collider experiment (!!!)
- Original note talks about collecting a large, inclusive sample of B's
- Design then focused on B to pipi
- Nowadays Bs mixing is the main goal
- Longer term, we're talking about ZH to nu nu b b, where b trigger allows a looser cut on the energy carried off by the neutrinos, and we gain an estimated 30% in Higgs acceptance
- Sometimes it is easier to know intuitively that a big technical step forward is a good idea than to know precisely what you'll use it for in the end

Problem synopsis

- Lower left DC tracks are input
- Lower right silicon raw data is input
- Lower center impact parameter is output
- We want it to "this" resolution and in "this" amount of time

A few of SVT's key techniques

- Emphasize parallel, pipeline (note that pipelining is temporal parallelism): nearly everything we do is (1) process in parallel, (2) fan-in the results
- Note that software SVT emulator takes tens of milliseconds per event (compared with hundreds of milliseconds for normal software silicon reconstruction): parallel processing and pipelining buy us 3 orders of magnitude

SVX-II

- detector symmetry lends itself to parallel processing
- there's even a partial radial symmetry: similar pitch, just different in size and location
- hence there are examples within SVT of $12 \times 6 \times 5 = 360$ -fold parallel processing, though most of SVT is just 12-fold symmetric

SVT data volume

- (don't worry, this is just to flash; I'd be a total geek to read the whole thing)
- point to physical size, 12-fold repetition (2 azimuthal slices per crate, plus two fan-in/out crates)
- the system does a HUGE data reduction: gigabytes/sec in, megabytes/sec out (whether you count peak or average throughput)

SVT symmetry reflects detector symmetry

- again, process in parallel, fan in the results: 12 azimuthal sectors in parallel
- sweep hand across top box to briefly illustrate flow: raw data into charge centroids; finding track candidates; linearized fitting; then on to the fan-in

Associative Memory working principle (like playing Bingo)

- SVT's second trick: clever pattern recognition
- note coarse binning (half millimeter road size vs 60um strip size)
- note that, for the illustrative case of straight-line tracks, the number of roads to consider scales as the inverse square of the road size
- each road ("pattern") is a coincidence of binned hits (one per layer)
- we do this (in parallel!!) by handing out a bingo card to each of 32768 players
- each binned hit is called out once, and the players mark their cards
- when the hits are done, the players whose cards are fully marked raise their hands, and are enumerated with a priority encoder
- so the execution time is linear in N_{hits} and linear in $N_{\text{matched roads}}$
 - sort of like "histogram search" software algorithm, as opposed to looping over pairs or triplets of hits

Our colleagues invested years in this Bingo game!

- This is quick: just point out that Luciano et al spent years developing a custom chip for this. If we were to begin anew today, we could do the same job in less area with commercially available programmable chips!

On linearized circle fit in an SVX wedge

- SVT's 3rd trick: linearized fitting
- This needs to be redone more neatly, concisely
- Note that linear fit doesn't mean that tracks are straight lines; it means that the coordinates measured by the detector are linearly related to the fitted track parameters (e.g. a polynomial fit is linear--can do with a matrix inversion)
- In real life, we derive the fitting constants from a monte carlo linear regression, but it's easy to see analytically how well the linear fit is expected to work
- You can see (lower right) that the linear fit gives $\tan(\phi)$, not ϕ
- There is a multiplicative error on d that grows as we move out from the center of the "wedge," but it's at maximum a 3.5% effect: 35um at outside of acceptance, 3.5um at trigger cut point
- Clear consequence of linearization is that d vs ϕ is piecewise linear, not sinusoidal (top right)

Track fitter: linearized fitting

- input 4 measurements; output c parameters and 3 numbers ("constraints") that you can square and sum to make chisquare
- given the covariance matrix (which we precompute), fit is a 6×6 matrix multiply
- More parallelization: matrix multiply is really one 6×1 dot product per parameter+constraint
 - do them in parallel in separate programmable chips
 - plus one more trick: use the road ID as a hint
 - allows you to do a fit every 250 nsec!!
- (This is a reasonable time to point out how powerful these programmable logic devices are, since I plan to skip all the junk below about beamline subtraction, how versatile the ghostbuster board is, etc.)
 - (By the way, we're probably going to use the GB as a trigger resonance detector, protecting SVX wire bonds)

~10us waiting for data, ~15 processing, and we're done

- Ta-dah
- not much to say here, but we did it

Et voila

- (need to get a better impact parameter plot)
 - should be more like 50um in a good plot
 - write numbers on slide
 - write $\sigma(\text{beam})=33\text{um}$ (or whatever)
 - what is offline d resolution?
- from the very first test runs big charm signals!

By the way

- Jonathan thinks I should note (verbally) that one example of such a design feature is ability to source/sink data at each pipeline stage: subsystems that had this feature were much faster to get working than subsystems that didn't

Onward!

- Speaks for itself

First year's SVT physics results

- (just an outline. Update for final content?)

Luminosity

- be prepared for tough questions here
 - where did the 180/pb delivered go? Why do we use 60?
 - What's wrong with the machine? What are the limitations?
 - What do we expect for luminosity now?

CDF's hot topic for 2002

- when the luminosity is low, you have to increase the cross-section
- now 300-400K D0 \rightarrow Kpi (have a PR plot?)
- we've surpassed FOCUS, e.g.
- that's my 12th night quote, even if they've seen it somewhere else!

Fraction of charm from b decays

- mention Chun's and Rolf's names (says Henry)
- 2 handles on b fraction:
 - b lifetime
 - b-c mass difference \Rightarrow charm gets a kick in different direction
 - ◆ gives pseudotrack an impact parameter
- plots show pseudotrack impact parameter, fitted to two different resolution models
- Ds has higher b fraction because virtual W readily makes Ds
- this is an important ingredient in a charm cross-section measurement

Charm cross-section

- unfortunately, this isn't blessed! Need to replace with something else
- if it had been blessed, it would have been nice to include a comparison with a calculation and a comment about b vs c xsec excesses
- I thought "blessed except for COT efficiency" had some implication for public plots page -- oops

Measure Cabibbo-suppressed decay rates

- from last summer
- if the charm xsec stuff is included, then one can contrast the detailed empirical characterization of the acceptance from last measurement with the first-principles modeling of this analysis, say nice things about reconciling them
- should be able to measure lifetime difference $KK, K\pi$ to get y_{mix} (how well?)

Measure D_s, D^+ mass difference

- mention Ivan's name
- 1st run2 paper!!
- The most sophisticated subsystem in CDF produced the first paper. (Hardware is easier than software?)
- Updated? Maybe include momentum scale tuning stuff?

D^0 to $\mu\mu$

- give Rob's name up front
- Using hadronic B trigger to search for leptonic charm decays!!

Analysis strategy

- maybe don't need to show this slide, just state some of the facts

Mass separation

- Need nicer looking plots; need to say what's what clearly.

Ingredients

- speaks for itself

Reference signals

- need pretty plots
- are numbers allowed?
- $K\pi$ may just be confusing? Well, illustrates important control sample.

K, π misid

- seems fine, need official plots

Sensitivity (closed box)

- Maybe I'm only allowed to wave my hands about the numbers?
- I think the projection, assuming small BG, is fair game, as well as comment about what we're doing to understand expected BG
- point out that we can probably stay ahead of BF

B_s flavor oscillations

- "Looking a bit toward the future ..."
- Experimenters love flavor oscillations (meson or neutrino) because one can write down a theory using undergrad quantum mechanics (or even an analogy using freshman mechanics--though I left out the damping)
- I think this is cute. Will they find it insulting? Should I add something more technical?

Toward Bs mixing

- need updated plots
- usual comment about boost resolution
- this is our yield in the easiest decay mode to study; other modes will follow
- how well are we doing? Yields? Tagging? Resolution? Luminosity?

“skip”

- This was from JDL’s Aspen talk. It implies that with O(1K) events, assuming nominal tagging (9%?), we can do $x=25$. Check this.

2-body hadronic B decays observed

- I need to learn how all of this works so that I don’t look stupid
 - both the experimental details and the method for extracting gamma
- Giovanni’s thing about mpipi and p2/p1 was cute, don’t need 4 mass hypotheses

Summary

- Henry says end instead on physics, hard numbers, not generalities

Misc notes

- run2, run2 record luminosities? How soon to 2/fb?
- How well on beta+gamma vs number of events?
- Mention bs to mumu: how well can we do?
- Find lake louise cleo talk on the web
- Belle B to pipi?
- Henry: the more numbers the better.
- Unki: How many *’s do you lose? (e.g. efficiency)
- $\lambda_{\text{B} \rightarrow \text{p} \pi^-}$ vs $\lambda_{\text{B} \rightarrow \text{p} \pi^+}$??
- How good is our PID? Vertex resolution? Momentum resolution?
- Joe recommends a slide explaining ingredients in a mixing measurement
- how much to “cleanup” cuts reduce D0 mumu combinatorial BG?
- What is an example of CPV in D0 decays?
- B to hh: $\sigma(\text{ideal})/\sigma(\text{CDF}) \sim 0.6$ (Kpi vs piK); ideal/babar ~ 0.8
- based on mass separation alone, we have $\sim 3\sigma$ evidence that we see something other than Bd to Kpi